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An Appraisal of Existing Room-Corner Fire Models

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ABSTRACT

Four fire growth models used to model the effects of room-corner fires are appraised using data obtained from a series of experiments involving full scale corner fire testing with four different interior linings. The room-corner models appraised are those of Wade (BRANZFIRE), Janssens, Karlsson and Quintiere.

The models are appraised on the basis of their ability to accurately predict the conditions in the compartment. The models of Quintiere, Janssens and Karlsson are pure flame spread models and as such only provide a prediction of heat release rate, (HRR) and upper layer gas temperature. BRANZFIRE is the only of the three incorporating a zone model so comparison can be made to interface height upper layer temperature and lower layer temperature in the experimental compartment.

The models provided by Karlsson and Janssens could not be run in an accurate manner so comparison had to be made on the basis of previously published data. BRANZFIRE was shown to predict the compartment conditions to a good degree of accuracy although the overall trend was to over predict the upper layer temperature and under predict accordingly the lower layer temperature and interface height. Both Karlsson and Quintiere's models are shown to grossly over predict the upper layer temperature. No temperature data was available for Janssens' model, but heat release rate comparisons to Quintiere and Karlsson indicate that this would also significantly over predict the upper layer temperatures.

It is concluded that BRANZFIRE provided the best fit to the experimental data and with its adaptability to a multitude of fire situations is the closest to becoming a useable fire engineering design tool. The current beta release does however require a great deal of further testing for validation purposes.

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NOMENCLATURE

Where possible nomenclature is presented to directly correspond to the source from which it was taken. As there seems to be no standard set of notation, some researchers define the same parameters differently. Accordingly where necessary the notation below is referenced to its source.

Δ	*Length of control volume (m)*
δ	*Thickness (m)*
λ_r	*Radiative fraction of energy loss by radiation from the plume of flame*
ρ	*Density (kg/m³)*
ρ_g	*Gas density (kg/m³)*
ρ_∞	*Ambient air density (1.18 kg/m³)*
σ	*Stefan-Boltzmann constant (5.66961 x 10^{-8} W/m²K⁴)*
φ	*Flame spread parameter (kW²/m³)*
τ	*Ignition time² (s)*
A_f	*Compartment floor area (m²)*
A_o	*Vent area (m²)*
A_p	*Pyrolysis Area (m²)*
A_s	*Compartment surface area (m²)*
c	*Specific heat (kJ/kgK)*
c_g	*Gas specific heat (kJ/kgK)*
c_p	*Ambient air specific heat (1.003 kJ/kgK)*
C	*Constant (2.2 for room-corner fires)*
C_N	*Constant (0.1 for Cooper's N% method where N = 10)*
g	*Acceleration due to gravity (9.81 m/s)*
h_c	*Convective heat transfer coefficient (W/m²K)*
H	*Ceiling height (m)*
H_o	*Vent height (m)*
Δh	*Change in enthalpy per unit mass (kJ/kgK)*
ΔH_c	*Heat of combustion (MJ/kg)*
k	*Thermal conductivity (kW/mK)*
k_g	*Gas thermal conductivity (kW/mK)*

$k\rho c$	*Thermal inertia (kW^2s/m^4K^2)*
L	*Heat of gasification (MJ/kg)*
L_f	*Height of triangular pyrolyzing region[13] (m)*
$\dot{m}_f$	*Mass loss rate of fuel (kg/s)*
$\dot{m}_o$	*Mass flow rate of hot gases through the vent (kg/s)*
$\dot{m}_p$	*Mass flow rate of air entrained into the plume (kg/s)*
M_u	*Mass of the upper layer (kg)*
N	*Constant (10.0)*
$\dot{q}''$	*Net energy transferred ahead of an advancing flame (kW/m^2)*
$\dot{q}''_e$	*External heat flux incident on a surface[3] (kW/m^2)*
$\dot{q}''_f$	*Heat flux from ignitor to ceiling[3] (kW/m^2)*
$\dot{q}''_f$	*Heat flux over pyrolysis area[6] (kW/m^2)*
$\dot{q}''_{gc}$	*Heat flux forward of the flame[2] (kW/m^2)*
$\dot{q}''_{ig}$	*Heat flux from the ignitor (kW/m^2)*
$\dot{q}''_{ig,r}$	*Radiative heat flux from the ignitor flame (kW/m^2)*
$\dot{q}_u$	*Net heat transfer to the upper layer*
$\dot{q}''_w$	*Heat flux from ignitor to lining material behind ignitor[3] (kW/m^2)*
$\dot{Q}$	*Total heat release rate (kW)*
$\dot{Q}''$	*Material heat release rate per unit area (kW/m^2)*
$\dot{Q}_f$	*Total heat release rate from the fire*
$\dot{Q}_{ig}$	*Ignitor heat release rate (kW)*
t	*Time (s)*
T	*Compartment temperature (°C or K)*
T	*Temperature (°C or K)*
T_b	*Bottom thermocouple temperature (°C or K)*
T_f	*Flame temperature[3] (°C or K)*
T_L	*Lower layer temperature (°C or K)*
T_{MAX}	*Maximum thermocouple temperature (°C or K)*
T_N	*Interface temperature (°C or K)*

T_o *Initial surface temperature*[3] *(°C or K)*

T_s *Surface temperature (°C or K)*

$T_{s,min}$ *Minimum surface temperature for flame spread (°C or K)*

T_u *Upper layer temperature (°C or K)*

T_v *Vapourization temperature (°C or K)*

T_∞ *Ambient air temperature (27°C or 300K)*

$\overline{V}$ *Mean velocity of flame front*[3] *(m/s)*

V_g *Ambient gas velocity (m/s)*

V_s *Flame spread velocity (m/s)*

W_b *Width of triangular pyrolyzing region*[13] *(m)*

$W_{1/2}$ *Width at half height of triangular pyrolyzing region*[13] *(m)*

x *Position*[3] *(m)*

x_b *Length of burned-out region (m)*

x_f *Flame length (m)*

x_p *Length of pyrolysis region (m)*

$x_{p,o}$ *Length of initially pyrolyzing region*[13] *(m)*

y_p *Height of pyrolyzing region*[13] *(m)*

$y_{p,o}$ *Height of initially pyrolyzing region*[13] *(m)*

Z *Height of layer interface from base of fire (m)*

z_p *Depth of pyrolyzing region*[13] *(m)*

1. INTRODUCTION

This research work has been performed in partial fulfilment of the requirements of the Masters in Engineering in Fire Engineering at the University of Canterbury. The research was conducted at the Building Research Association of New Zealand (BRANZ) under the supervision of Colleen Wade.

1.1. BACKGROUND

In order to determine the fire hazard associated with given materials testing and experimental procedures have been available for some time. Currently however the test methods employed are primarily of the reaction to fire type and are largely designed to classify materials into a rank order, assigning to specific materials a classification, usually in the form of an arbitrary number (for instance on a scale of 0 to 100) or letter. Such classifications are of limited use and in fact tell us little about the actual fire properties of the material[1].

There have been moves however to change this and to more accurately determine the fire properties of materials. Greatest advances have come in the areas of structural elements and more recently, but to a lesser extent, furniture and furnishings. Combustible wall and ceiling linings however have only just begun to draw attention from researchers who have now standardised bench-scale and full-scale test methods in order to better understand the fire performance of these materials.

Major advances in this field are primarily due to research efforts in Sweden, conducted as a joint venture between Lund University, the Swedish National Testing and Research Institute and the Swedish Institute for Wood Technology Research. Additionally, in a project named EUREFIC the National Fire Testing Laboratories of the Scandinavian countries (Sweden, Denmark, Finland and Norway), have carried out considerable research in the field of combustible wall lining materials[1].

This research has brought about the evolution of new modelling techniques with the specific aim of predicting the fire hazard associated with combustible wall and ceiling linings. The models in general rely on data from modern bench-scale flammability tests as input and from this attempt to predict full scale fire growth.

With regards to the hazard associated with lining materials the major consideration is flame spread across the material, and more specifically the flame spread under ceilings and in wall-wall and wall-ceiling intersections. These areas may be addressed principally by conducting analysis of room-corner fire experiments. The difficulty in describing such modes of flame spread has meant that at present no definitive model exists. There are however models available which vary in their degrees of sophistication and user input which attempt to describe these complex phenomena, thus, the purpose of this research is to appraise and report on the effectiveness of four such models.

The four models which have been chosen for analysis are the those of Quintiere, Karlsson, Janssens and Wade (BRANZFIRE). All are similar in their basic approach to the problems of room-corner flame spread and associated hazard development modelling but deal with them differently by way of making various assumptions and simplifications.

In the appraisal of the models it is necessary to build a database of room-corner fire data involving a series of full scale experiments, and bench-scale material data from cone calorimeter testing. This data, coupled with additional data from the Swedish and EUREFIC research gives the ability to provide meaningful comparisons between the models and thus appraise each on their merits.

1.2. THESIS STRUCTURE

To Appraise the models an attempt has been made to follow the method outlined by Nelson et al.[26], this involves the 5 following elements:

1. Examination of the basic principles involved and approaches used by the models being investigated.

2. Choosing a set of model output results that demonstrate the effectiveness of the model.

3. Selection of a well characterised and measured test series having the input and output data.

4. Execution of fire simulations using the models being evaluated to produce the results of interest.

5. Comparison of results.

Thus the structure of the thesis is as follows:

Chapter 2 provides background information on the general approach needed to model room-corner fires, that is the modelling of the appropriate flame spread and fire development.

Chapter 3 provides a discussion into the actual ways in which each model approaches its solution, detailing the input required and equations and assumptions made in its analysis of any given situation.

Chapter 4 introduces the experimental techniques used to obtain full scale fire and material property data. This is broken down into two main parts, the full scale room-corner fire testing and the bench-scale testing using the cone calorimeter. All relevant details of the experimental procedure are included in an effort to aid in later validation or reproduction.

Chapter 5 is a description of the methods used in the gathering and reducing of the data. A collation of the reduced data from the experiments and important input variables are presented and observations detailed for later comparison to the models.

Chapter 6 outlines the modelling procedure, discussing such things as model options, defaults and parameters chosen in the modelling process.

Chapter 7 introduces the comparison of the models examining the accuracy to which each can predict a real life situation (represented by the full scale room-corner experiments carried out at BRANZ). Major inconsistencies between models are highlighted and explanations as to the reasons for these presented.

Chapter 8 builds on the information presented in Chapter 7 and provides an objective appraisal of the models tested.

Chapter 9 outlines the conclusions from the appraisal, drawing upon these to make recommendations as to any perceived improvements which may be necessary for the models. The models are ranked as to their performance in relation to each other and the experimental results. Based on this future work is recommended in some areas in which the models may be seen as deficient.

2. BACKGROUND INFORMATION

To appraise the four models for room-corner fire scenarios it is first necessary to understand the fundamentals of flame spread and associated fire development and the basic nature of the room-corner fire itself. Accordingly this chapter provides appropriate background information, in no way does it attempt to fully explain the intricacies of this complex field, therefore where possible more extensive treatments of the subject are referenced.

2.1. GENERAL FLAME SPREAD THEORY

2.1.1. CONCURRENT FLOW FLAME SPREAD

Flame spread in the direction of the predominant ambient air flow is known as concurrent flow flame spread (also known as wind-aided flame spread), and is shown diagrammatically in Figure 1. This mode of flame spread occurs naturally in an upward direction due to warm buoyant air rising, thus, this is the most important mode of flame spread to account for when considering burning up a vertical wall surface[36]. It is also important to note that this is generally the fastest mode of flame spread.

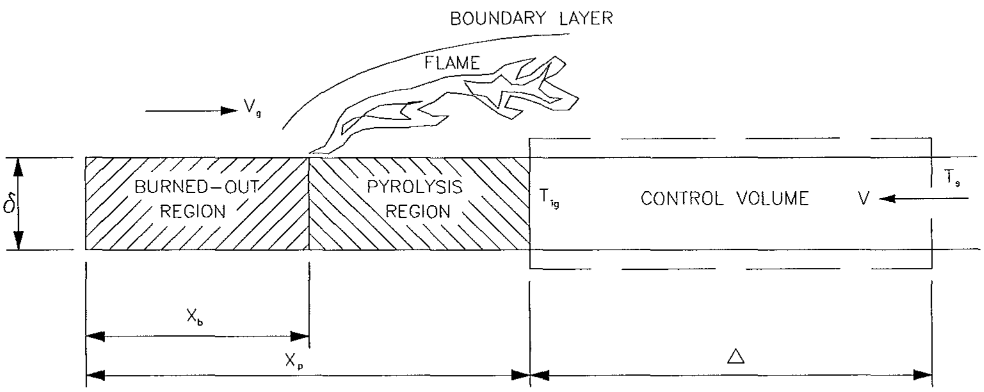


Figure 1: Concurrent Flow Flame Spread Model[2]

Factors which determine the rate of flame spread are principally the orientation of the fuel, the direction and nature of the flow and the fuel thickness[3]. When considering the thickness of the fuel a distinction may be made between two main cases, thermally thin and thermally thick. Thermally thin denotes a case where the temperature of a solid is considered to be uniform throughout its thickness. Thermally thick analysis implies a temperature gradient through the thickness of the material. In the case of flame spread along wall and ceiling linings only the thermally thick assumption is considered for discussion and analysis.

The aim of the flame spread analysis is to be able to predict important parameters in the development of a fire. These parameters are velocity and time to ignition. The analysis begins with a statement of the fundamental equation of flame spread. This equation considers the net energy (heat) transferred (per unit area per unit time), $\dot{q}''$, ahead of the advancing flame to heat the medium from its initial temperature, T_s, to its ignition temperature, T_{ig}. This energy is equated to the change in enthalpy (per unit area per unit time) that the medium experiences for an observer on the moving flame front[2]. For steady conditions,

$$\rho V \Delta h = \dot{q}'' \qquad \text{Equation } 1^2$$

Solving Equation 1 for velocity with the inclusion of forward gas phase conductive heat transfer as developed by Quintiere[2] yields,

$$V_s = \frac{dx_p}{dt} = \frac{x_f - x_p}{\tau} \qquad \text{Equation 2}$$

where τ is the ignition time associated with the flame heat flux.

This may be equated with Equation 3, another well known equation for the time to ignition of a semi-infinite material exposed to a constant surface heat flux to yield the velocity Equation 4,

$$\tau = \frac{\pi k \rho c \left(T_{ig} - T_o\right)^2}{4\dot{q}_e''^2}$$ Equation 3[3]

$$\overline{V} = \frac{4\dot{q}_e''^2 \left(x_f - x_p\right)}{\pi k \rho c \left(T_{ig} - T_o\right)^2}$$ Equation 4

2.1.2. *Opposed Flow Flame Spread*

Opposed flow flame spread occurs when the ambient air flow is against the direction of flame propagation, such as downward or lateral spread on a vertical surface.

Once again beginning with the fundamental flame spread equation, Equation 1, and assuming the dominant heat transfer mechanism to be forward gas phase conduction gives,

$$V_s = \frac{\dot{q}_{gc}''^2 \Delta}{k \rho c \left(T_{ig} - T_o\right)^2}$$ Equation 5

Quintiere[3] also assumes that the forward gas phase conduction should be equated to the opposed flow convection,

$$\rho_g c_g V_g \frac{\partial T}{\partial x} \sim k_g \frac{\partial^2 T}{\partial x^2}$$ Equation 6

Combining this assumption with Equation 5 Quintiere and Harkleroad[2] found,

$$V_s = \frac{\varphi}{\pi k \rho c \left(T_{ig} - T_o\right)^2}$$ Equation 7

where φ is a material property known as the flame spread parameter defined as,

$$\varphi = V_g (k \rho c)_g \left(T_f - T_{ig}\right)^2$$ Equation 8

This may be determined from a bench scale test exposing a vertical sample to an external radiant heat flux, i.e. as is done using the LIFT apparatus[2].

2.2. ROOM-CORNER FIRES

At present the majority of data which exists regarding compartment fires pertains to ventilated compartments with a design fire located in, or close to, the centre of the room. This is also true for most of the plume and ceiling jet correlations. However the occurrence of a fire in a room-corner is not only common in many real life fires it is also the most severe location for the fire in terms of hazard development.

In the previous chapter flame spread was discussed generally assuming an unconfined surface with no edge effects or radiation from anything but the flame front. When looking at a room-corner fire it is essential that modelling takes into account the intersections between wall-wall, and wall-ceiling, indeed the mere presence of a ceiling has a significant effect on the rate of fire development[3]. The main effects of a ceiling on compartment fire growth are[4].

- The hot layer developing beneath the ceiling radiates to room surfaces which increase the heat flux onto already pyrolysising surfaces, which in turn increase the burning rate.

- Flame extension beneath the ceiling causes radiation view factors between the flame and the fuel to increase which also increase the heat flux incident on the fuel and the burning rate of the fuel.

- A combustible ceiling allows concurrent flame spread to occur beneath the ceiling, the associated heat release rate contributes further to the fire.

- Flame extension along the wall-ceiling intersection results in downward opposed flame spread from the top of the wall which also contributes to the heat release rate.

A generalised schematic showing the basic modes of flame spread in a room-corner is shown in Figure 2 below.

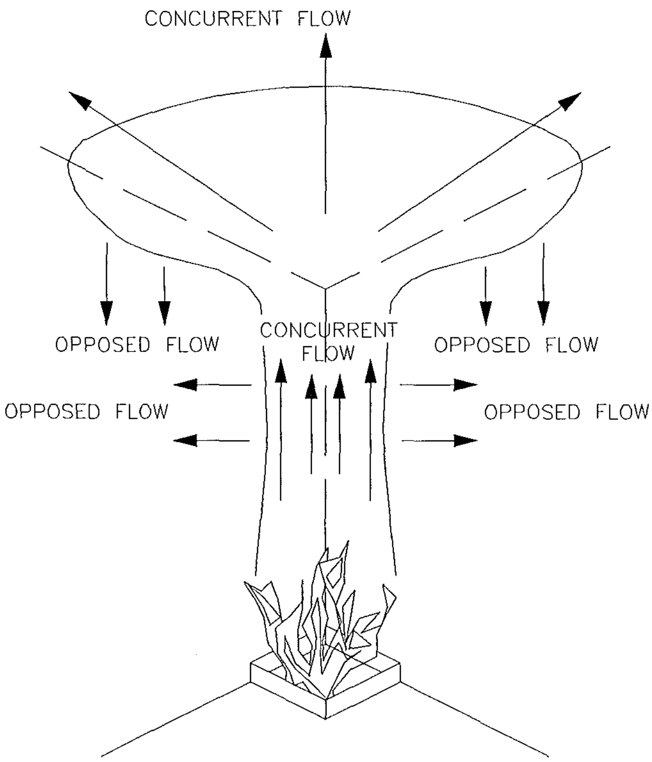


Figure 2: Principle Modes of Flame Spread In a Room-Corner Fire

2.3. Room-Corner Fire Modelling: A General Approach

In order to model a room-corner fire it became necessary to first design a standard test method by which the models may be verified and evaluated, this is now known as the ISO 9705 Large Scale Test for Evaluation of Surface products[1], and is shown in Figure 3. This uses a room measuring 2.4m by 3.6m by 2.4m high with a 0.8m by 2.0m doorway opening in one of the walls. A gas burner is placed in the far corner of the room, used as an ignition source. Typically the burner heat release rate (HRR) is initially 100kW rising to 300kW if ignition has not occurred within 10 minutes of starting the test. The HRR of the room is determined from oxygen consumption measurements in the exhaust gases which go from the open doorway into an exhaust hood, this method is described further in Chapter 4.

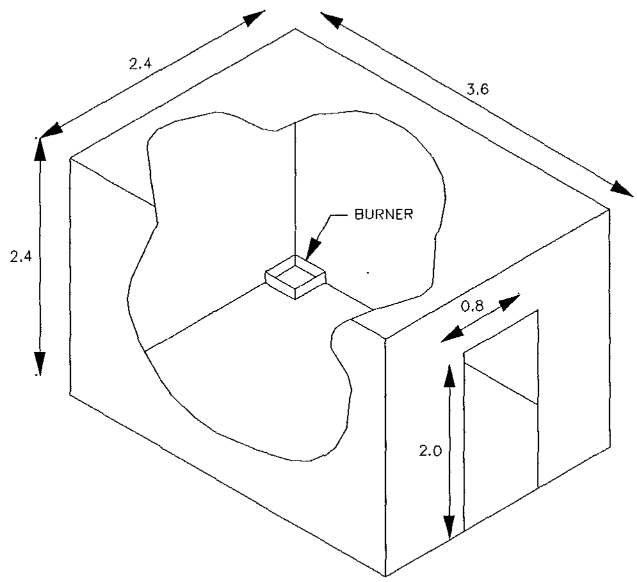


Figure 3: ISO 9705 Room-Corner Test Setup

The full scale testing of lining materials in this way is time consuming and cost prohibitive thus a great advance in this area has been the development of models which can predict the fire hazard development in the compartment with data provided from bench-scale tests. Such tests are usually done with the use of a cone calorimeter, in accordance with ISO 5660[22]. This test requires a 100mm by 100mm sample of the lining material to be subjected to cone calorimeter testing at various levels of irradiance, typically 75 kW/m^2, 50 kW/m^2, 35 kW/m^2, 30 kW/m^2, 25 kW/m^2, 20 kW/m^2, and 15 kW/m^2. The HRR measured from these tests may then be used to determine properties of the material crucial to modelling. These are the materials thermal inertia, $k\rho c$, and the ignition temperature of the material, T_{ig}. This is described further in Chapter 4.

The general approach taken to modelling room-corner fires has been to first predict the rate of (concurrent) flame spread up the wall given the HRR and other material properties found through bench-scale testing of lining materials. From this information and by analysis of the vent flows through the door or vent, data can be obtained as to the actual HRR and temperatures in the compartment. This information is also used for the prediction of smoke and general emission modelling to quantify the hazard in the compartment over time.

3. Modelling of Room-Corner Fires

Several attempts have been made to model room-corner fire scenarios in the past. The first, conducted at Ohio State University (OSU), was completed by Smith between 1980 and 1987. This model was designed to simulate fire growth on walls in a compartment and therefore lends itself to direct comparison with standard room test results[5].

The model consisted of two sub-models. The first calculated the dimensions, temperature, and velocity of the plume by applying conservation equations. The second calculates the upper layer temperature and interface height from a mass and energy balance for the layer. Input is in the form of a material energy release rate from a dynamic calorimetry apparatus[6].

Janssens[7] found there to be several inadequacies in both the physical basis and program structure of this model and even some errors, accordingly the model was revised by Janssens who produced a modified version of the model known as MOSURF (**M**odified **O**hio **S**tate **U**niversity **R**oom **F**ire model). This model also proved to be inaccurate and research into this model has now been abandoned.

3.1. Quintiere

Following on from work by Karlsson and Magnusson[8], Quintiere and Cleary[9] presented a simple but complete accounting for all modes of flame spread which govern growth on a wall and ceiling. Although successful agreement was found with data their model lacked a direct accounting of room thermal feedback and selected energy release data from the cone calorimeter at an arbitrary irradiance level. A development from this was a new model which attempted to eliminate these limitations[6].

The revised model simulates the ignition, flame spread, burn-out, and burning rate of wall and ceiling materials subject to a corner fire ignition source in a room[6]. It considers both opposed flow and concurrent flow flame spread in different regions. Concurrent flow is assumed up the vertical walls, spread along the ceiling and spread along the ceiling jet located in the wall-ceiling intersection. In these cases the equations for the flame spread are identical and no distinction for the differing configurations has been made. Similarly there is no configuration distinction for opposed flow flame spread expressions which govern the lateral spread along the walls and the downward spread from the ceiling jet. All modes of flame spread may be seen in Figure 2.

For the purposes of deriving the HRR both heat flux from the flame and radiative feedback from the room are taken into account. For the flame the heat flux is taken as uniform over two distinct areas. Over the pyrolysis area associated with the burner ignition a value of 60 kW/m^2 is used. For the area associated with the extended flame, which governs the upward flame spread, a value of 30 kW/m^2 is used. These are rational assumptions supported by Williamson et al.[10], although the actual heat flux from the flame depends on the size of the burner, the flame height and the type of fuel supplied.

In looking at the contribution of the room thermal feedback constant room surface and layer temperatures are assumed, these are also maximised to give an upper limit for its effect. Quintiere finds here that the thermal feedback effect is not significant compared to the flame heating effects until conditions representative of the onset of flashover, i.e. an upper layer gas temperature of 500°C and a corresponding blackbody irradiance of 20 kW/m^2. Thus a more detailed representation may not be needed.

Ignition occurs when the temperature of the material, T_s, is equal to the ignition temperature, T_{ig}. Burning is then assumed to follow up the wall at a width equal to that of the burner and proceed into a ceiling jet at the intersection. The depth of this ceiling jet is taken from Alpert's study of axysymetric ceiling jets[11] to be 0.08H, where H is the ceiling height, this is approximated to be of constant depth.

Quintiere's assumption that the effects of thermal feedback are not significant during the early stages of fire growth leads to a further conclusion that the most simple representation for the upper layer gas temperature is sufficient for the model. This, he believes, eliminates the need for a comprehensive analysis by compartment zone or field models. Accordingly the temperature correlation of M^cCaffrey et al.[12] is used, where,

$$T = T_\infty \left\{ 1 + C \left[\frac{\dot{Q}}{\rho_\infty \, c_p \sqrt{g} \, T_\infty \, A_o \sqrt{H_o}} \right]^{\frac{2}{3}} \left[\frac{\sqrt{\frac{k \rho c}{t}} \, A_s}{\rho_\infty \, c_p \sqrt{g} \, T_\infty \, A_o \sqrt{H_o}} \right]^{-\frac{1}{3}} \right\} \qquad \text{Equation 9}$$

The value of C is taken as 2.2 for corner fires, as opposed to 1.63 for centred fires due to the lower rate of air entrainment.

The total HRR from the burner and combustible wall and ceiling is given by,

$$\dot{Q}(t) = \dot{Q}_{ig} + \dot{Q}'' A_p(t) \qquad \text{Equation } 10^{12}$$

According to Quintiere the rate of heat release may be considered constant at any instant in time and uniform over the pyrolysis area. The relationship for $\dot{Q}''$ is developed in terms of peak values of $\dot{Q}''$ found in the cone calorimeter for different irradiance levels. Plotting the peak HRR per unit area against the external heat flux supplied by the cone calorimeter revealed a linear relationship with the slope of the line known to be $\Delta H_c/L$, where ΔH_c is the heat of combustion and L the effective heat of gasification. Quintiere now assumes that $\Delta H_c/L$ is an effective material property which enables the computation of peak values of HRR under all heat flux conditions by Equation 11,

$$\dot{Q}'' = \frac{\Delta H_c}{L}\left(\dot{q}_f'' - \sigma T_{ig}^4 + \sigma T^4\right) \qquad \text{Equation 11}$$

Thus drawing on the earlier assumption of a burner heat flux of 60 kW/m^2 this value can be equated to $\dot{q}_f''$.

The pyrolysis area is computed from the configuration of the pyrolysis and burnout fronts. The pyrolysis area can be seen in Figure 4 and requires the solution of four ordinary differential equations, one integral equation and one algebraic equation. For a complete description of the equations and the solution methodology Quintiere's paper[6] is recommended.

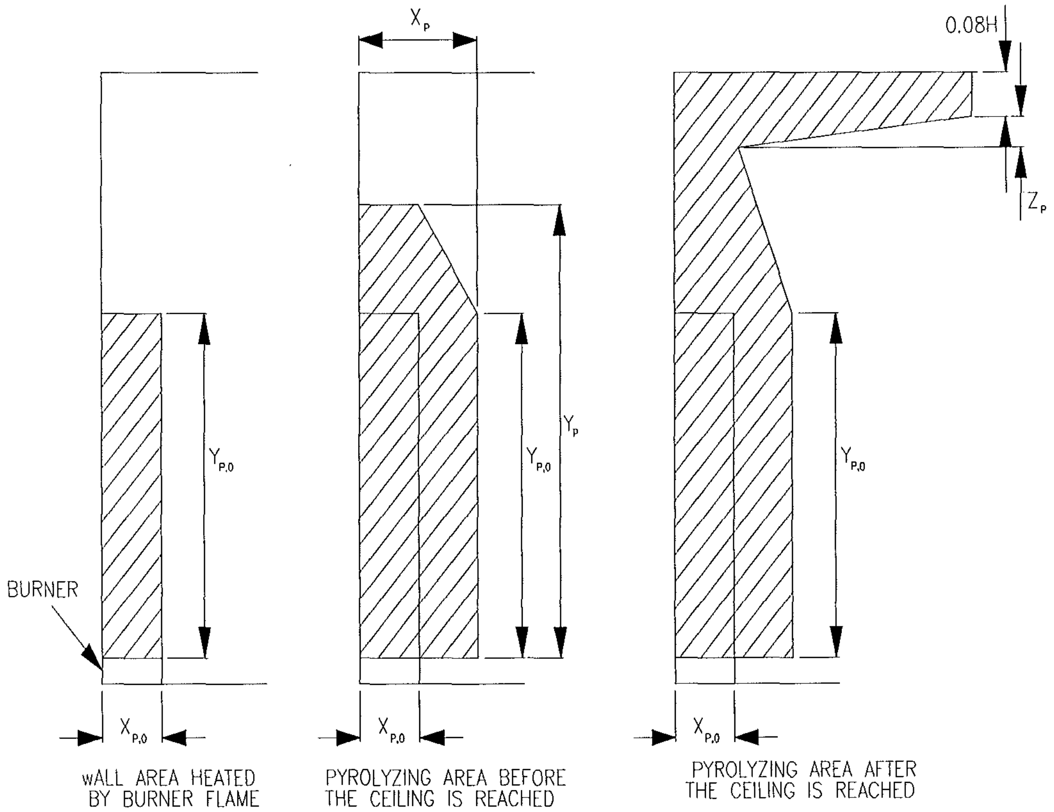


Figure 4: Quintiere's Model of the Room-Corner Fire Pyrolysising Area[13]

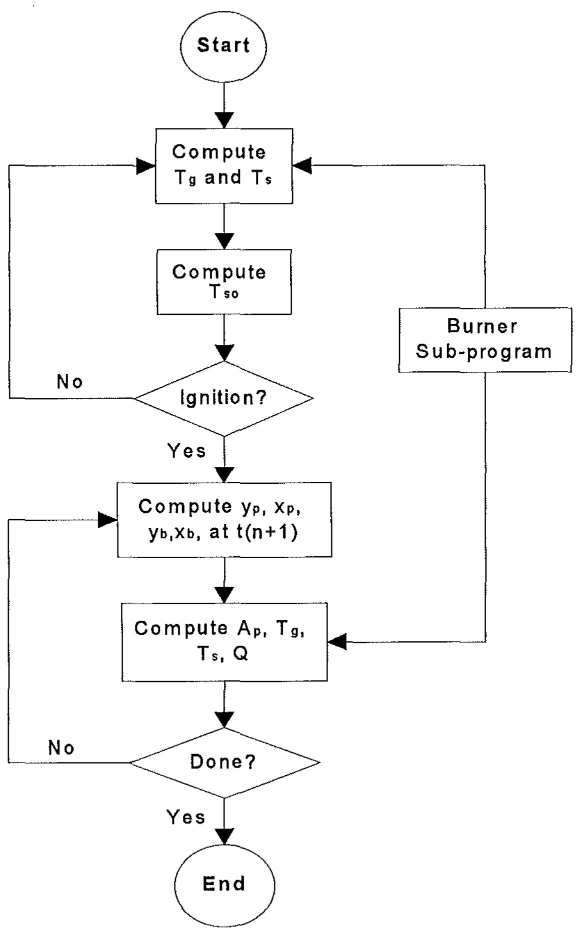


Figure 5: Flowchart Representing Quintiere's Model[13]

3.2. JANSSENS

As part of a three year[i] international research project under the auspices of the US-Slovak Science and Technology Program with the title 'Room-Corner Reaction to Fire of Wood and other Building Materials" Marc Janssens, in conjunction with Ondreg Grexa, Robert White and Mark Dietenberger produced a modified version of Quintiere's model to simulate room-corner fires. Initially the project focused on the computer model developed at the Ohio State University (OSU) culminating in the development of MOSURF (Modified OSU Room Fire Model)[5,7]. However a detailed analysis of the OSU model[7,28] revealed several major problems in the physical basis of the model and hence a decision was made to abandon it. The

[i] Project scheduled for completion in September 1997

development in the meantime of models by Karlsson (described below) and Quintiere (described above) provided and alternative to MOSURF and it was decided that Quintiere's model should be used for further development.

The model follows Quintiere's method leading to Equation 9 as a representation of the upper layer gas temperature, and Equation 10 for the total HRR. The modifications to Quintiere's model come in the way in which $y_{p,0}$ and $\dot{q}''_{ig}$ are chosen.

As far as the geometry of the flame is concerned Janssens reasons that the rectangular area chosen by Quintiere to represent the area heated by the burner would be better approximated by a triangular area as shown in Figure 6 below. This in turn would be characterised by a height L_f and a width at half the height, $W_{1/2}$.

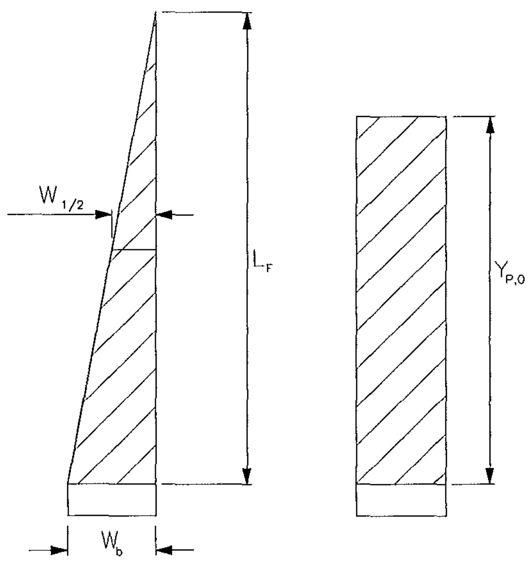


Figure 6: Janssens' Triangular Heated Area, as Opposed to Quintiere's Rectangle[13]

The flame boundary and hence values for the parameters was found by Janssens et al.[13] to occur at the 600°C isotherm, thus for the HRR's of the Nordic and ASTM burners the appropriate geometrys were found.

Quintiere uses a constant heat flux from the flame of 60 kW/m^2, whilst he refers to this as a rational assumption based on work by Williamson, Janssens has deduced through advanced heat transfer principles heat flux values which result in significantly lower values. These are summarised in Table 1 below.

Burner Type	$\dot{Q}''_{ig}$ **(kW)**	$\dot{q}''_{ig,r}$ **(kW/m^2)**	h_c **(W/m^{2}K)**	$\dot{q}''_{ig}$ **(kW/m^2)**
Nordic	100	34.7	13.8	44.4
Nordic	300	36.0	15.9	47.1
ASTM	40	22.4	10.8	29.9
ASTM	160	29.5	12.9	38.5

Table 1: Janssens Calculated Heat Flux Data for Standard Burners[13]

In addition to the above modifications Janssens makes the following modifications

- Approximation of the complex pyrolysising area of Quintiere (see Figure 4) with rectangles for simplification of radiative heat transfer calculations.

- The assertion by Quintiere that the surface temperature remains at T_{ig} for the burning period is thought to significantly underestimate the effects of re-radiation, therefore a user specified vaporisation temperature T_v is incorporated.

- The surface emissivity of 1 has been replaced by a user defined value for consistency with analysis of bench-scale ignition data.

- The two additional differential equations to determine the burnout area were replaced with a simple book-keeping procedure. As soon as an incremental area ignites the model keeps track of the cumulative heat release. When this exceeds the total heat release of the material, as specified by the user, the incremental area is assumed to be extinguished[13].

3.3. KARLSSON

In his PhD. thesis, 'Modelling Fire Growth on Combustible Lining Materials in Enclosures', (Lund University, 1992), Karlsson provides two mathematical models in an attempt to describe compartment fire growth due to a room-corner fire scenario. The models are referred to as Model A and Model B. Model A models the case of combustible wall lining materials on both walls and ceilings with Model B only describing the case of combustible lining material on the walls only. Karlsson compares his models to experimental data from both full scale and 1/3 scale experiments.

Karlsson's flame spread model follows the same initial basis as presented in Chapter 2 and derives in that manner Equation 3 for the time to ignition. The approach Karlsson takes to solving the flame spread equations can be divided into two distinct methods. The first is an analytical solution, the second, used for the more complex flame spread cases Karlsson solves numerically, stating however:

> *"The disadvantages of a numerical solution are that the physical meaning of the terms get somewhat clouded and the behaviour of the solution cannot be directly analysed."*[1]

but also:

> *"The advantages of a numerical solution are that material HRR can be taken directly from the cone calorimeter, flame height can be expressed as a non-linear function of HRR and pre-heating of the material by the gas layer can be taken into account".*[1]

For the purposes of this thesis only Karlsson's Model A will be examined as it is the more complete in that it models a combustible ceiling with the wall linings. Model A considers a total heat release which is assumed to come from three sources, the gas burner, pyrolysis from the vertical area behind the burner and pyrolysis from the ceiling and ceiling-wall intersection[14]. Karlsson's model accounts for the hot upper layer of the compartment to heat the lining material surfaces and thus allowing the flame to spread more rapidly. Two key points to note are that Model A does not take into account the opposed flow flame spread both laterally and downward (illustrated in Figure 2), as he[1] and Quintiere[6] have found that this mode of flame spread is insignificant until close to the onset of flashover. Model B, although modelling only the wall lining, does model both concurrent and opposed flow flame spread.

The following sub-models are included in the total simulation model[14]:

- Ignition of the wall area behind the burner.

- Upper layer hot gas temperature calculation based on calculated heat release.

- Heating up of the ceiling and wall areas immersed in the gas layer.

- Ignition and flame spread under the ceiling and in the ceiling-wall intersection.

- Calculation of total HRR based on the areas pyrolysising and the time dependence of bench-scale HRR curves.

Material properties input data and geometric input data to Model A[22] are:

- HRR as a function of time from the cone calorimeter at an incident heat flux of 50 kW/m^2. This heat flux was chosen for consistency since all materials had been tested at this level. A somewhat lower level may however be more appropriate for the full scale scenario.

- The early part of the cone calorimeter data describes conditions before the material ignites, this part of the data is not used in Model A. Ignition is assumed to have occurred when the HRR reaches 50 kW/m^2 and the time when this occurs is taken to be $t = 0$.

- Material parameters $k\rho c$ and T_{ig} are determined from bench-scale tests.

- Length, breadth and height of the room and height of opening, height and width of gas burner.

- Modelling parameters relevant to the full-scale room, i.e. $\dot{q}''_w = 45$ kW/m^2 and $\dot{q}''_f = 35$ kW/m^2, where $\dot{q}''_w$ is the irradiant heat flux from the burner flame to the lining material behind the burner and $\dot{q}''_f$, the heat flux from the flames to the ceiling.

3.4. WADE (BRANZFIRE)

Most existing fire zone models generally do not account for the ignition and burning of wall and/or ceiling lining materials and thus may underestimate the actual rate of fire development, and subsequently the hazard, in cases where combustible room linings are present[3] Wade claims to address this deficiency with BRANZFIRE by incorporating a single-room zone model fully integrated with a flame spread and fire growth model applicable to a room-corner fire scenario.

The model relies on the flame spread models of Karlsson or Quintiere, (user specified), described above, but differs from the work of both to include the changes in room surface temperature as significant input into the model. BRANZFIRE deals with this phenomenon by incorporating a zone model to predict the temperatures of the surfaces and uses this as further input to the flame spread model. A flowchart showing the input to the BRANZFIRE model may be seen in Figure 7 below. Quintiere[6] specifically rules out the use of zone or field models in the prediction of these temperatures, claiming them to be insignificant in the stages of early fire development, i.e. up to flashover.

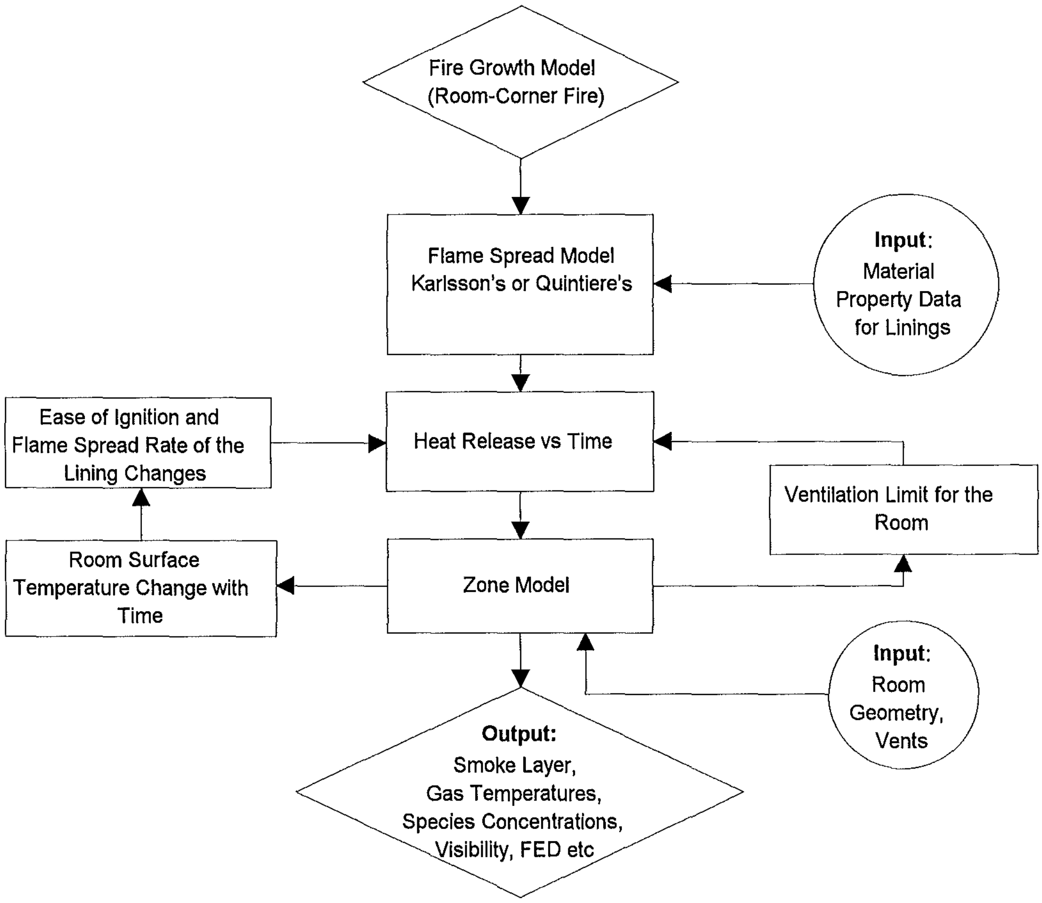


Figure 7: Flowchart of the BRANZFIRE Model[3]

3.4.1. BRANZFIRE'S ZONE MODEL

A zone model is a compartment fire model based around the central assumption that the gases in the compartment are divided into two distinct layers or zones, namely a hot upper layer and a cooler lower layer. Each of these layers is assumed to be uniform with the fire plume providing the mechanism for transport of pyrolysised mass from the fuel and entrained air from the lower layer to the upper layer. The thermodynamic (including species concentrations) conditions of the zones therefore may be calculated by the solution of a number of conservation equations applied to each zone and compartment vents.

TEMPERATURE OF THE UPPER LAYER

As stated above conservation equations are utilised to determine thermodynamic properties, thus in the upper layer to solve for temperature it is first necessary to solve for the mass flow in the upper layer, shown below,

$$\frac{dM_u}{dt} = \sum_{objects} \dot{m}_f + \sum_{objects} \dot{m}_p - \sum_{vents} \dot{m}_o$$ Equation 12[3].

Wade now makes the following assumptions:

- $\dot{m}_f$ is much less than $\dot{m}_p$ and thus can be considered negligible.
- The mass from the fuel, including the burner, wall and ceiling linings involved in the fire is assumed to originate from the location of the burner.

By application of the Steady Flow Energy Equation the temperature of the layer may be deduced from a mass balance and is found to be

$$\frac{dT_u}{dt} = -\frac{T_u\left(c_p(T_u - T_L)\sum \dot{m}_p - (1-\lambda_r)\sum \dot{Q}_f - \dot{q}_u\right)}{\rho_\infty T_\infty c_p A_f (H - Z)}$$ Equation 13

Similarly an expression for the lower layer temperature may be deduced.

Having found an expression for the temperature variations in both the upper and lower layers the next step is to incorporate this information into radiative and conductive heat transfer calculations. This, coupled with the heat flux from the regions of flaming combustion, it is thought, would more accurately describe the actual HRR in the compartment.

HEAT TRANSFER

BRANZFIRE's treatment of radiation exchange follows the method described by Forney[15] and accounts for radiation transfer between the upper and lower walls (portions of the wall in the upper and lower layer respectively), and the floor and ceiling. Also accounted for is the emission of radiation by soot particles and absorption by carbon dioxide and water vapour. For this model Wade makes the following assumptions[3]:

- Both gas layers of each wall are assumed to be at a uniform temperature. This is generally not true where the surfaces meet each other.

- The surfaces and gas layers are in quasi-steady state, remaining constant over the duration of the time step of the associated differential equations.

- For the purposes of estimating the radiation heat transfer from the flame the total fire is assumed to radiate uniformly in all directions from a single point source.

- The radiation emitted by the room surfaces, gas layers and the fire is assumed to be diffuse and grey (i.e. the radiant flux is assumed independent of direction and wavelength).

- The room surfaces are assumed to be opaque (i.e. incident radiation is either reflected or absorbed, not transmitted) and the gases are assumed to be non-reflective.

- The room is assumed to be a rectangular box with each surface either perpendicular or parallel to every other surface. radiation losses through the room openings are ignored.

Wade follows in detail Forney's method to solve the net radiation equations as a matrix corresponding to a set of linear equations, this method is beyond the scope of this thesis, however Forney[15] is recommended to readers who require a full treatment of this subject.

The conduction of heat at the wall, ceiling and floor surfaces was solved using an implicit one dimensional 20 node finite difference scheme. As above a detailed explanation of this is not required here but reference is made to Incropera and de Witt[16] for complete analysis. The important aspect to note is that a set of nodal temperatures over any given time steps may be compiled starting with prescribed initial conditions.

ADDITIONS

BRANZFIRE, by virtue of its incorporation of a zone model, is also able to determine species concentrations in the layers consequently allowing tenability to be assessed. This is done on the grounds of user specified visibility limits at a specified layer height in a method proposed by Beyler[17], and the toxicity of the products of combustion in a method outlined by Purser[2].

4. Experimental Procedure

In comparing the models to experimental data it is necessary to ensure that there is a certain degree of uniformity between the experimental procedure in each case. In previous research outlined above the verification of models has been based mainly on data gained in the EUREFIC research which applies the NORDTEST[1] standard room-corner fire test. Where this has not been the case the data has often been compared to data from the ASTM[1] standard test. Both of these methods are recognised in ISO 9705. In this case the setup differs considerably from these standard fire tests and is outlined below.

Far from being a source of uncertainty it is thought that the differences in the experimental setup here and the more subtle differences in the two previous test methods mentioned above provide a more stringent test of the models. That is, it tests the models under more than one, condition so more meaningful comparisons may be made and limits of the applicability of the models can be found. In that respect it is vital that different experimental methods are utilised.

4.1. Bench-Scale Cone Calorimeter Testing

Material properties which are required as input to the model were determined using the BRANZ cone calorimeter. In this process 100mm square samples of the material are conditioned and tested. To comply with the ISO standard for bench-scale testing, ISO 5660, the samples are conditioned for a week in a constant climate environment at a temperature of 20°C and a relative humidity of 65%. The materials were then tested in the cone calorimeter with piloted ignition at irradiances ranging from 75 kW/m^2 to 35 kW/m^2. The data taken was the time to ignition and the heat release rate. For each material three replicates were tested to ensure consistency, data was then averaged and key parameters found.

In the course of previous research carried out at BRANZ both Gypsum Plasterboard and Fibreboard had been tested hence it was only necessary to test the fire retardant Fibreboard and Hardboard materials. Cone calorimeter data may be seen in Appendix 6.

4.2. FULL SCALE ROOM-CORNER TESTING

Prior to this research there had been one previous full scale room-corner fire experiment conducted at BRANZ. This was carried out as part of Wade's dissertation[3] in an attempt to verify the BRANZFIRE model. The experimental setup for this has been modified somewhat to incorporate more thermocouples, the position of the thermocouples was also adjusted in order that the readings better reflect the conditions in the compartment.

4.2.1. THE TEST COMPARTMENT

The compartment in which the experiments were conducted was a bedroom located in an experimental house facility located at BRANZ. The room itself was 3.16m long by 2.73m wide by 2.40m high, a single vent 1m high by 0.405m wide, was located in one of the walls at a sill height of 0.82m from the floor. The room was lined with 25mm of Gypsum Plasterboard on the walls and ceiling, the floor was constructed form 25mm flooring grade particleboard.

The lining material tested was placed over the entire ceiling, and in the corner of interest. In addition to this it was decided that the lining material also be placed along the top of the corner walls were the ceiling jet was likely to occur. This was not done in the initial test.

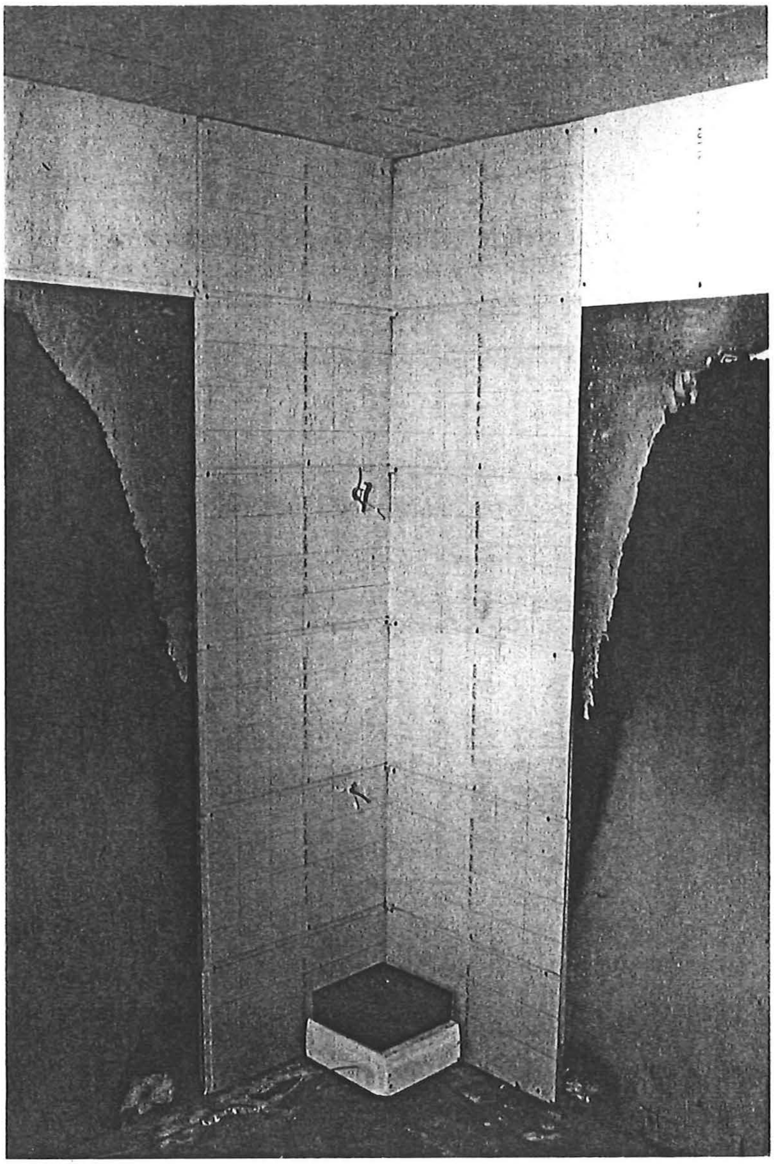


Figure 8: Experimental Lining Material Setup

4.2.2. INSTRUMENTATION

In the previous experiment floor to ceiling thermocouple trees were placed arbitrarily in the middle of the room. It is now thought that there are definite areas in the room where the thermocouple readings will more accurately reflect the conditions in the compartment. These locations suggested by Janssens and Tran[19] are found in the quiescent region in the corners of the compartment, and also in the vent. Whilst Janssens and Tran recommend that thermocouple spacing be equidistant from floor to ceiling this level of sophistication is not available with limited channels available in the data logger. Accordingly there are 8 thermocouples per floor-ceiling tree and these are spaced as shown in Figure 9.

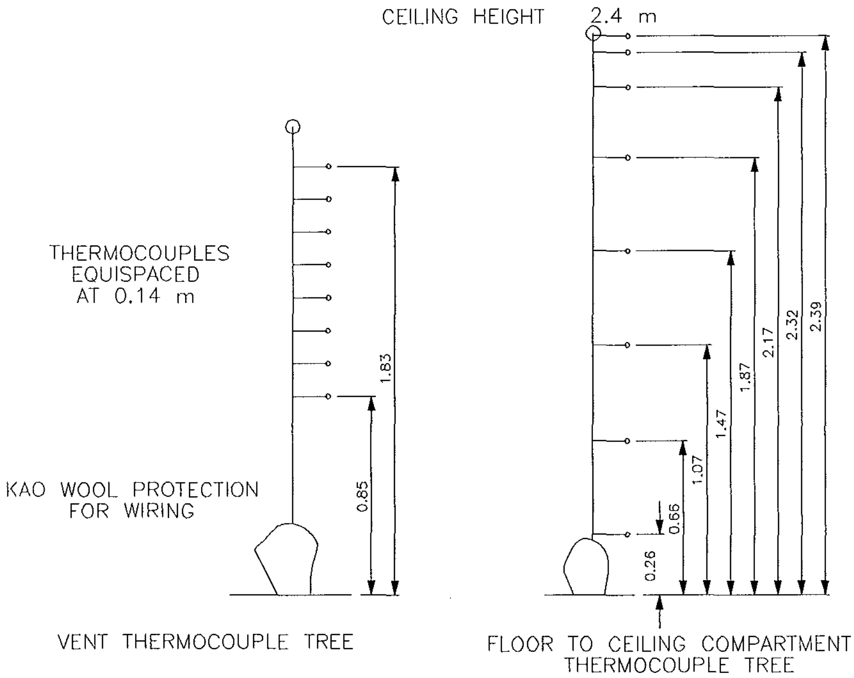


Figure 9: Experimental Thermocouple Tree Setup

In addition to the thermocouples further instrumentation is used in the compartment in the way of two Gardon type heat flux meters, these were both placed in the wall so as to be directly in contact with the flame during the experiment.

4.2.3. The Burner

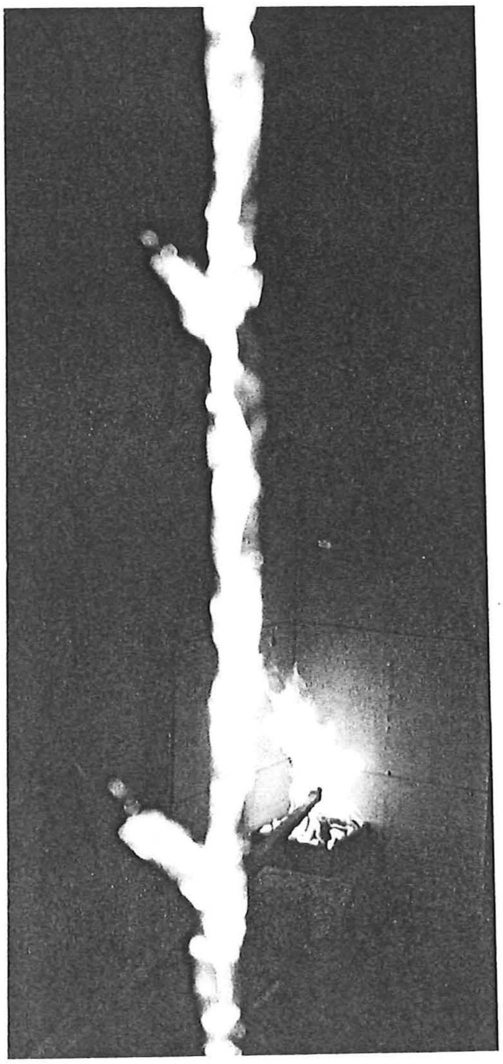
The burner was in the form of a square pan 250mm by 250mm containing industrial grade hexane (trade name Pegasol 1516). This was placed on a load cell in the corner. The Heat of Combustion (ΔH_c) of the hexane was measured to be 42.9 MJ/kg using the cone calorimeter.

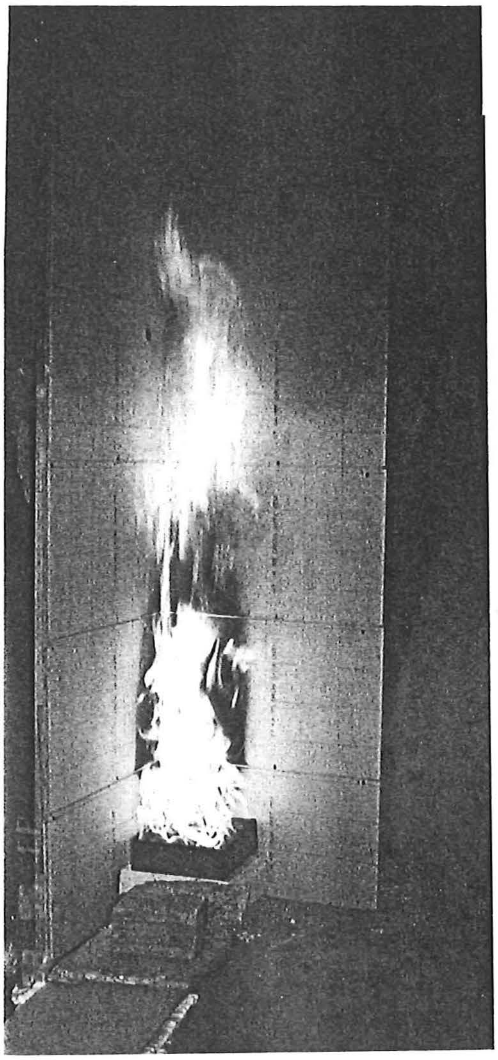
5. Experimental Results

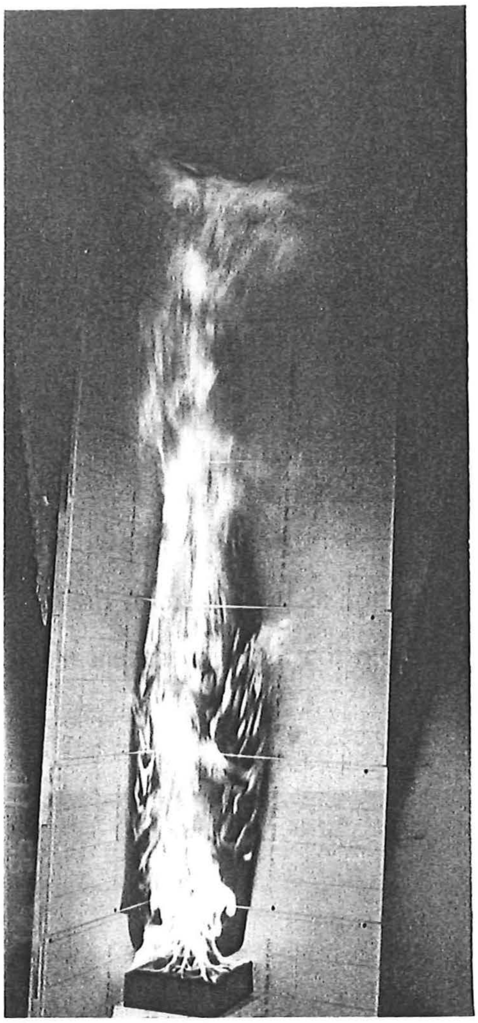
The experimental results are summarised here and briefly discussed, raw data pertaining to each experiment may be seen in Appendix 1.

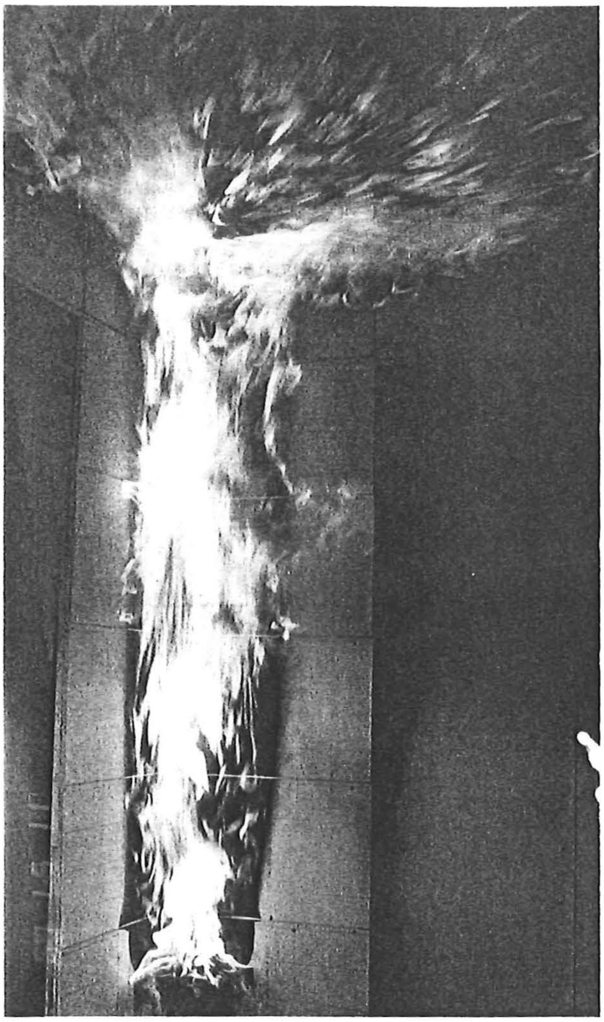
5.1. Observations

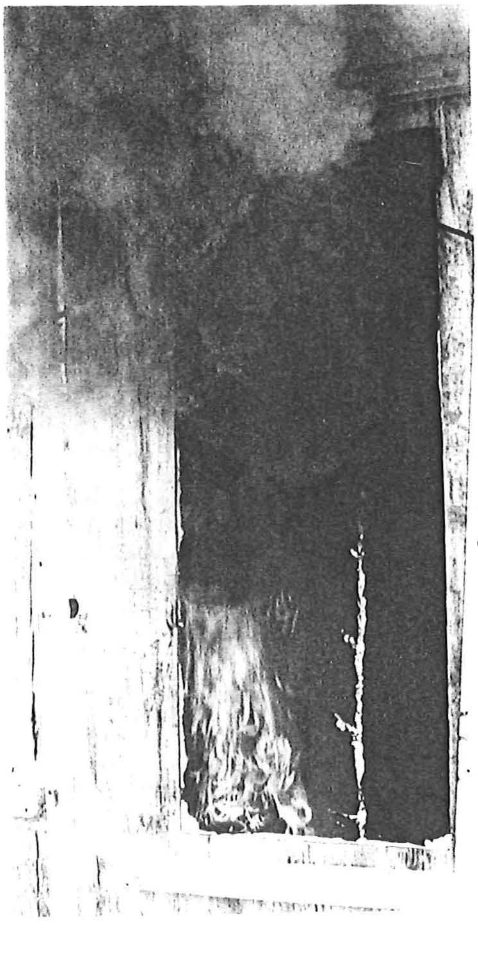
Observations for the individual experiments are included in Table 2 below. The photographs below are designed to give a visual indication as to the size of the fires in the experimental program. These pictures come from the first experiment using Fibreboard.

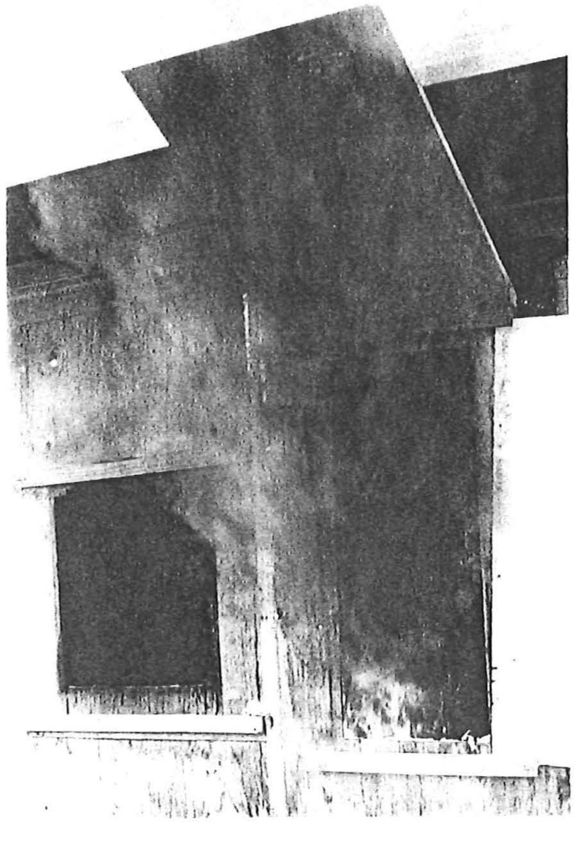












Experiment Description	Observations
Experiment 1	
Fibreboard Tiles (13mm)	Rapid flame progression up corner Well developed ceiling jet Smoke filling forces layer below vent sill Ventilation limit reached, excess pyrolyzates ignite outside vent opening
Experiment 2	
Fire Retardant Fibreboard Sheet (12.5mm)	Debris fell from ceiling into pan The room TCT fell to the floor with a complete sheet of the material Fuel burnt out at around 410 seconds Flux meter short circuited in the middle of the test but then corrected itself
Experiment 3	
Hardboard (6mm)	Pan filled rapidly with small pieces of debris from the walls adjacent to the flaming region The fire was extinguished through a lack of oxygen but then reignited when sufficient oxygen became available.
Experiment 4	
Non Paper Faced Gypsum Plasterboard (25mm)	No material ignited, burning was limited to the hexane source

Table 2: Experimental Observation Summary

It is important to note that the duration of each experiment differed considerably and that although some were still burning data logging had to be stopped at stages where debris caused significant obstruction to the measuring equipment or when thermocouple trees collapsed from the ceiling.

5.2. DATA REDUCTION

Data was logged during each experiment, with measured voltages being converted to actual temperature, heat flux and mass loss data through the use of a Quick Basic program developed by Peter Collier at BRANZ. In order to reduce the noise in the readings data points were logged at 5 second intervals with the points logged being the arithmetic average of the readings taken within that 5 second period.

Having collected the raw data it was possible to then compute the variables being used for comparison with the models, namely interface height, upper layer temperature and lower layer temperature. Although there are several means of evaluating these variables it was deemed to be most appropriate in this case to use the *N%* (where *N* was taken to be 10), method suggested by Cooper et al[21,18], evaluating the interface height and layer temperatures from the data gathered from the centrally located room thermocouple tree. Another method considered was that suggested by Mitler[26] this method determines the interface height 'a priori', via a freehand determination of the inflection point. This was deemed to be unsuitable for two reasons. Firstly due to the large quantities of data which needed to be reduced. Secondly the method, as presented, seemed to require more temperature readings per thermocouple tree if the variability of the interface height was to be reduced to an acceptable level.

Cooper's method defines the interface height in the compartment as the point at which the measured air temperature is equal to the temperature, T_N,, and is determined by comparison of T_N with the measured temperature profile. This is given in Equation 14,

$$T_N = C_N \left(T_{MAX} - T_b\right) + T_b \qquad \text{Equation 14}$$

The height at which this occurs must be found by interpolation as no continuous temperature distribution can be measured. Having found the location of the interface height it is then possible to define the layer temperatures with an averaging integral.

The integral may be evaluated numerically as the temperature distribution is not continuous.

Although this method involves interpolation and numerical solving of integrals, Peacock[18] quotes the averaged uncertainty for a series of large scale test measurements in a multiple room facility, between the 95% confidence limits as less than 16%.

Radiation correction of the thermocouples as suggested by Dembsey et al.[38] was not attempted as aspirated thermocouple probes were not available. Dembsey reports that this correction reduces the bare bead thermocouple temperature in the lower layer, whilst increasing the temperature in the upper layer. Although the correction has been reported as being of the order of 5-10% it would be prudent to attempt to incorporate this correction in further experiments. In the case of the BRANZ experimental program it was considered to be negligible. A sample calculation of the upper layer and lower layer temperatures and the interface height is given in Appendix 2.

Heat flux meters were used in the experiment as described above. The purpose of this was to measure the heat flux from the flame to the adjacent corner walls. As described above the value of this heat flux varies between models from 35 kW/m^2 to 60 kW/m^2.

During the course of the experimental program it became apparent that these meters were sensitive but also problematic in there operation mainly due to the fact that they relied on a water cooled surrounding jacket to ensure they performed adequately. Each meter was calibrated in the cone calorimeter in order to determine the calibration coefficient for each. In the case of the first calibration a coefficient of 15-24 could have been justified for one of the meters thus the validity of this data may be questionable. In subsequent calibrations the coefficients were far more stable but the variability between experiments became unsettling. In the second experiment the insulation covering the wire from the meter melted causing a short circuit and loss of a great deal of the data. In the third experiment the water cooling system failed and although this did not affect the meter's ability to record data the validity of this is again open to question. Having taken this into account it was decided that the data from these meters was inconclusive. This data is however included in graphical form in Appendix 1 with the other raw data collected during the experiments.

Data also used for comparison was taken from the research of Karlsson[1] in which he conducted full scale room-corner fire testing of 21 Swedish and EUREFIC materials. This series of experiments was conducted in accordance with ISO 9705 and reported data is available for both HRR and upper layer gas temperature. Data however was only available in graphical form and thus the accuracy is reduced.

6. MODELLING

6.1. BRANZFIRE

Modelling the results using BRANZFIRE was a relatively simple task for most materials. The process involved assembling relevant material data from the available references and utilising the cone calorimeter data to find other key material parameters. In each case it was attempted to keep the run duration consistent with that of the actual experiment.

Using the cone calorimeter input data BRANZFIRE calculates the ignition temperature, T_{ig}, and the thermal inertia, $k\rho c$, of the material using the method proposed by Janssens[1] for thermally thick solids. If there is justification that the material will not behave in a thermally thick fashion then it is important that some other method of finding these parameters be found. In the case of the two materials tested in the course of this research it is thought that the Hardboard may not have behaved as a thermally thick solid, hence the difference in the values found by experiment and those given in literature. Further research into this may be needed and perhaps the properties in the future should be found using the LIFT apparatus.

These parameters were found to vary significantly with the choice of time to ignition values in the cone testing (see Appendix 3). Time to ignition in the cone calorimeter testing is a subjective observation made by the operator who records the time that he or she believes the sample ignited. Therefore an alternative approach was used to determine the time to ignition, this was taken as the time at which the HRR of the material reached 30 kW/m^2. This time remained within 1-2 seconds of the observed time however this difference became important in the end evaluation of the $k\rho c$ parameter, this is shown in the sensitivity analysis of this parameter in Appendix 3.

Having compiled data from both observed and 30 kW/m^2 criteria using Janssens method as calculated by BRANZFIRE further data was also gathered from other references, namely that of Quintiere[2] and the Swedish Fire Testing Program[20], this is summarised in Table 3 below. One important point to note is that all of the T_{smin} data was obtained from published literature.

Model	T_{ig} (°C)	$k\rho c$ (kW^2s/m^4K^2)	T_{smin} (°C)	Source
EXP1A.mod	218.5	0.442	90[20]	Observed
EXP1B.mod	284.2	0.202	90[20]	30 kW/m^2
EXP2A.mod	131.4	2.809	210[2]	30 kW/m^2
EXP2B.mod	131.4	1.942	210[2]	Observed
EXP2F.mod	355	0.460	210[2]	Quintiere
EXP3A.mod	298	1.870	170[2]	Quintiere
EXP3B.mod	190.2	2.055	170[20]	30 kW/m^2
EXP4A.mod	469	0.515	380[20]	Swedish (s4)

Table 3: Model Identification and Material Property Data for the BRANZFIRE Model

Other basic input required into the model is the room material's thermal properties for the purposes of heat transfer calculations. This proved to be difficult for two reasons. Firstly the walls were only lined from the ceiling down to 600mm below, and this only on two walls of the compartment. Not being able to account for this in any complete manner it was decided to approximate the walls as being constructed fully from Gypsum Plasterboard. Secondly a problem occurred when looking at the ceiling construction. Although it was fully lined with the material being tested this was spaced 25mm from the 25mm Gypsum Plasterboard room lining. Here it was assumed that the heat transfer across the material would be over a relatively short period of time and as such the material being tested would govern the rate of any such heat transfer. Hence the ceiling was deemed to be constructed from the appropriate material being tested.

BRANZFIRE incorporates two different flame spread models, those of Karlsson and Quintiere. It also incorporates the Plume correlation's of M^{c}Caffrey and Delichatsios. Attempts were made to appraise the model with all combinations of these methods. It became apparent that when using the plume correlation of Delichatsios oxygen content in the compartment dropped to essentially 0%, from this arose computational difficulties within the model[34]. These problems have been rectified with a 0.01% lower limit put on the oxygen available within the compartment[33]. As this problem was rectified after analysis had begun in all modelled cases the plume correlation of M^{c}Caffrey has been used.

In terms of the heat flux to the wall and ceiling in the absence of any good quality data from the heat flux meters (see Chapter 5) the default values in each model are used for simulation. These default values, in the case of BRANZFIRE are those proposed by Karlsson and are discussed in Chapter 3.

BRANZFIRE allows for the HRR of the burner to be entered as a series of HRR pairs. The graphs representing these pairs may be seen in Figure 10 - Figure 13 below.

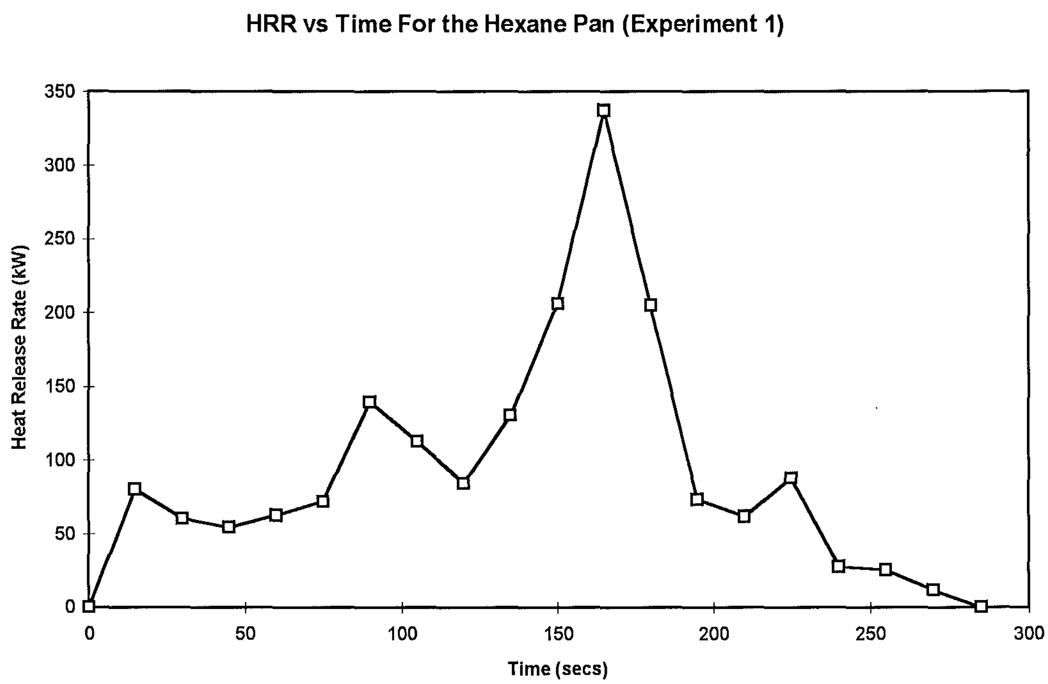


Figure 10: Experiment 1, Ignitor Heat Release Rate

BRANZFIRE incorporates two different flame spread models, those of Karlsson and Quintiere. It also incorporates the Plume correlation's of McCaffrey and Delichatsios. Attempts were made to appraise the model with all combinations of these methods. It became apparent that when using the plume correlation of Delichatsios oxygen content in the compartment dropped to essentially 0%, from this arose computational difficulties within the model[34]. These problems have been rectified with a 0.01% lower limit put on the oxygen available within the compartment[33]. As this problem was rectified after analysis had begun in all modelled cases the plume correlation of McCaffrey has been used.

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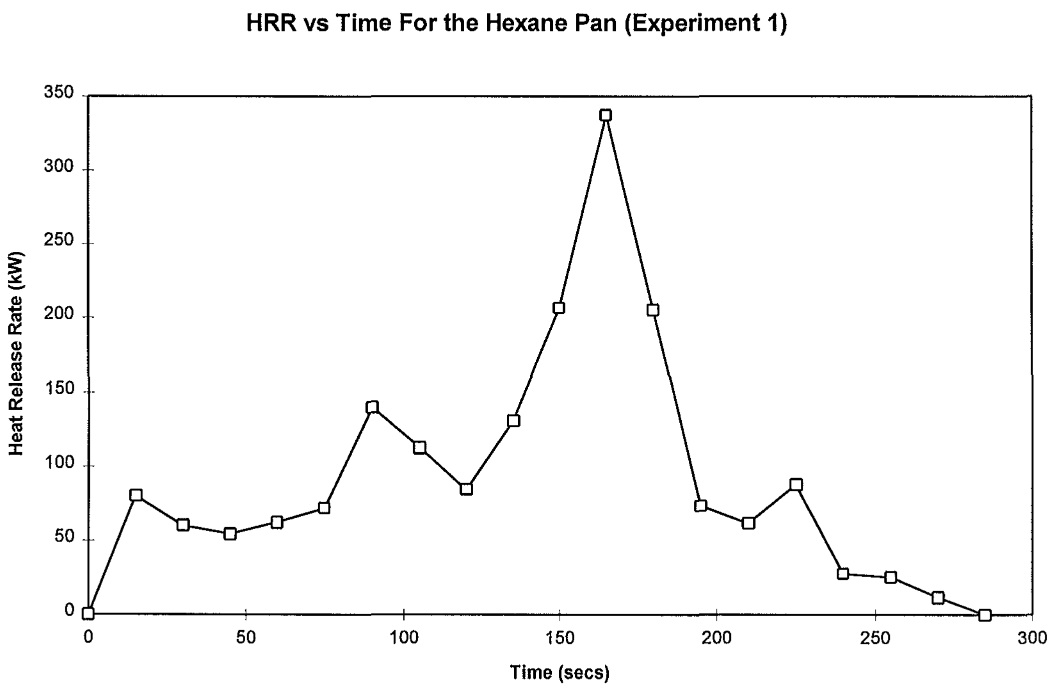

Figure 10: Experiment 1, Ignitor Heat Release Rate

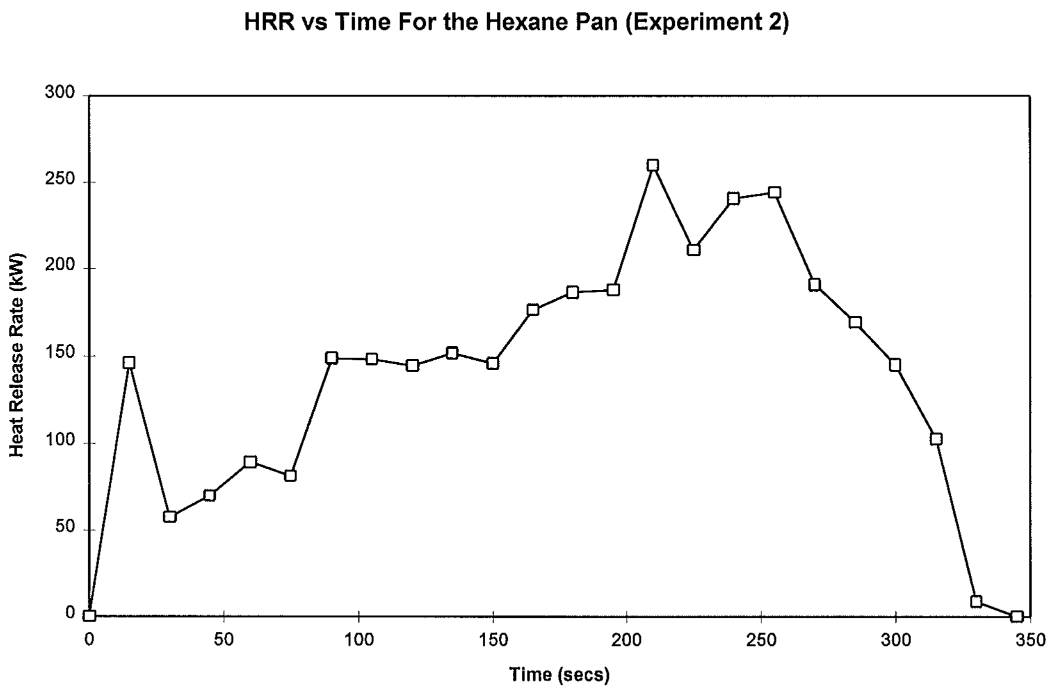

Figure 11: Experiment 2, Ignitor Heat Release Rate

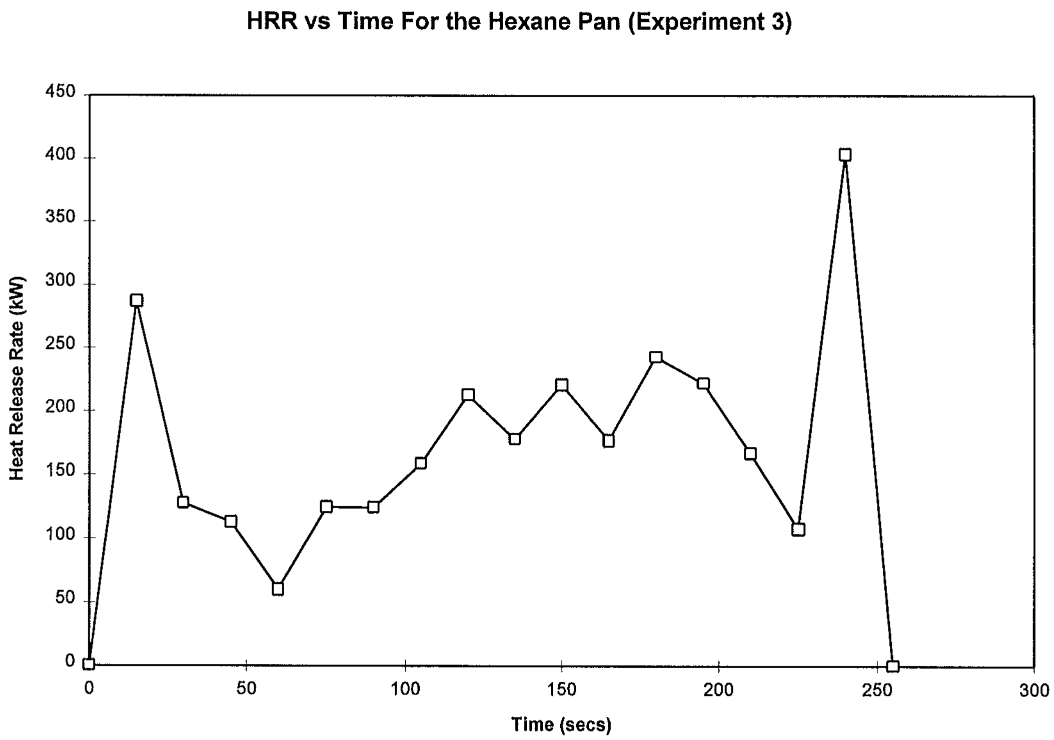

Figure 12: Experiment 3, Ignitior Heat Release Rate

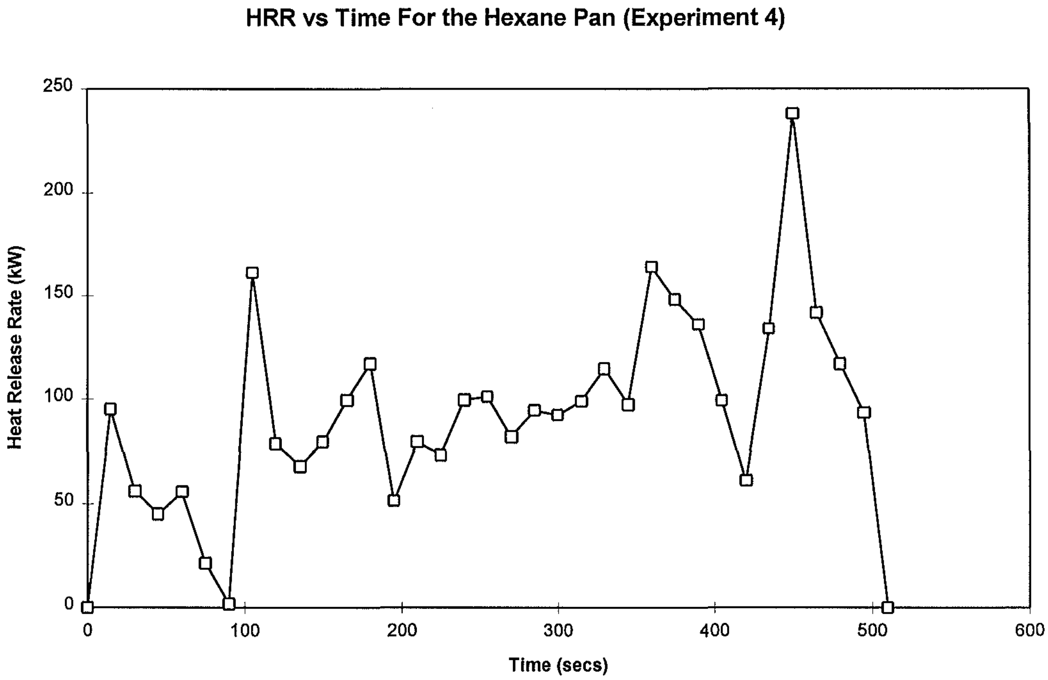

Figure 13: Experiment 4, Ignitor Heat Release Rate

Further summaries of model input and output may be seen in Appendix 1.

6.2. QUINTIERE

Quintiere's model predicts various conditions inside a compartment subject to a room-corner fire. This model is based on the ISO 9705 standard fire test and as such requires the heat release rate supplied from the burner to be entered as a constant value with the option given of a step change up in HRR if flashover does not occur within a specified time. In order to maintain a constant HRR during such an experiment it is essential that a gas fired burner be used. This presents difficulties in the case of the experimental program carried out at BRANZ due to the fact that the HRR from the hexane pan was far from constant. To facilitate modelling, the HRR from the hexane pan was averaged to get values ranging from 97 to 183 kW between the four experiments.

Quintiere's model gives little in the way of scope to change the analysis, unlike BRANZFIRE, thus models which were run for each experiment varied only in the values of T_{ig} and $k\rho c$ chosen. The values of these parameters are shown below in Table 4.

Model	T_{ig} (°C)	$k\rho c$ (kW^2s/m^4K^2)	Source
EXP1A.csv	218.5	0.442	Observed
EXP1C.csv	284.2	0.202	30 kW/m^2
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EXP2C.csv	355	0.460	Quintiere
EXP3A.csv	298	1.870	Quintiere
EXP3B.csv	190.2	2.055	30 kW/m^2
EXP4A.csv	469	0.515	Swedish (s4)

Table 4: Model Identification and Material Property Data for Quintiere's Model

A central difference between the BRANZFIRE and Quintiere models is the lack of any zone model in Quintiere's. Instead it serves to be principally a flame spread model where significant output is the geometry and temperature of the pyrolysis area and the HRR from the compartment. As it is not a zone model, and assumes an ISO 9705 or similar setup, there is no allowance for a vent with a sill height greater than 0, i.e. it models door type vents only. No interface height or lower layer temperature is calculated, however as described in Chapter 3 an average upper layer gas temperature is calculated as per Equation 9. Therefore this becomes the only variable available for direct comparison to the BRANZFIRE model and the BRANZ experimental program.

When initially examining the data it became apparent that the early temperatures given in the output were significantly higher than initially anticipated. Shortening the time step between result reporting revealed that the temperature after 0.1 seconds was typically around 60 - 70°C, significantly greater than the ambient temperatures. This was found to be typical however of the correlation which is designed to predict temperatures in a steady state fire and thus the time at which the correlation becomes valid is after around 5 - 10 seconds.

Whilst checking the computer code a discrepancy was found between the gas temperature correlation (Equation 9) used and that reported in Quintiere's paper[6]. The exponent on the second bracket was reported in the journal article as 1/3 as opposed to the correct -1/3[1,2,37]. This is corrected in another of Quintiere's et al papers[37]. This discrepancy also appears when Janssens[13] directly quotes Quintiere, using the incorrect form of the equation in his own research, the incorrect value of 1/3 follows and is henceforth used consistently throughout. This was corrected in the model code so is not one of the errors in his model. Karlsson when stating Equation 9 in his PhD.. dissertation[1] gives the exponent correctly as -1/3.

Input data from modelling using Quintiere's model is shown in Appendix 5.

6.3. KARLSSON

This model was supplied without instruction or explanation further than what was available from the relevant published papers[1,14,22,25,39] this made the user interface and input difficult to follow, this is further discussed in Chapter 7.

The model subsequently proved to be impossible to run due to probable errors in the source code which could not be identified. However some of Karlsson's PhD. modelling results[1] are available for comparison. Within these results there is data for Swedish materials s1 and s4 which correspond to the Fibreboard and the Gypsum Plasterboard used in the experimental program so these may be compared. As these results are for experiments as per ISO 9705 it was necessary to remodel the two materials with the appropriate changes in both Quintiere's and BRANZFIRE models.

6.4. JANSSENS

Some way into the modelling it was determined that Janssens model also contained errors in the code as it was unable to reproduce results quoted in published material[13,30,31]. This conclusion was supported by an independent researcher using the model in the United States[ii]. It is expected that a new release of the model will be in circulation some time in 1997 upon completion of the US-Slovak Science and Technology Program research.

The limited data which is available for comparison extends only to HRR modelling, which although comparable to Quintiere and Karlsson is not directly comparable to the BRANZFIRE output for the purposes of the thesis.

[ii] Lt. Andrew Grenier, U.S.C.G.

7. Comparison of Results

Appraisal of the models considered extends to the comparison of the interface height, UL (upper layer) temperature and LL (lower layer) temperature.

In the absence of independently modelled data from the models of Janssens and Karlsson comparison can only be made to previously published results.

7.1. Fit to Experimental Data

7.1.1. BRANZFIRE

To appraise the models it is first desirable to ascertain the standard set of parameters which will be used to give the most representative and comparable results. In this case it requires a choice between which flame spread model to use within BRANZFIRE, i.e. Karlsson or Quintiere.

The differences between using Karlsson's flame spread model and Quintiere's is small in the initial stages (0 - 300 seconds), with similar maximum and minimum values. Further from that Quintiere appears to model the fire more realistically in that it will predict a cooling of the layers, whereas Karlsson's model seems to merely plateau. For this reason the results provided for appraisal are all taken from modelling using Quintiere's flame spread model.

As discussed above the variability of the $k\rho c$ and T_{ig} values means that for effective comparisons to be drawn consistent data must be used. Thus the models which determine these parameters using the 30 kW/m^2 criteria are used, where this is not available, i.e. in the case of Gypsum Plasterboard, the Swedish values of Sundström[20] have been used. These models are EXP1B.mod, EXP2A.mod, EXP3B.mod and EXP4A.mod.

The following is a set of summary graphs which help demonstrate the effectiveness of the model to predict full scale room-corner fires.

N.B. The data for the actual experiments is graphed as it was logged, at 5 second intervals. The BRANZFIRE output however is graphed at time steps of 15 seconds. The line markers are shown only for the purposes of distinguishing the two sets of data.

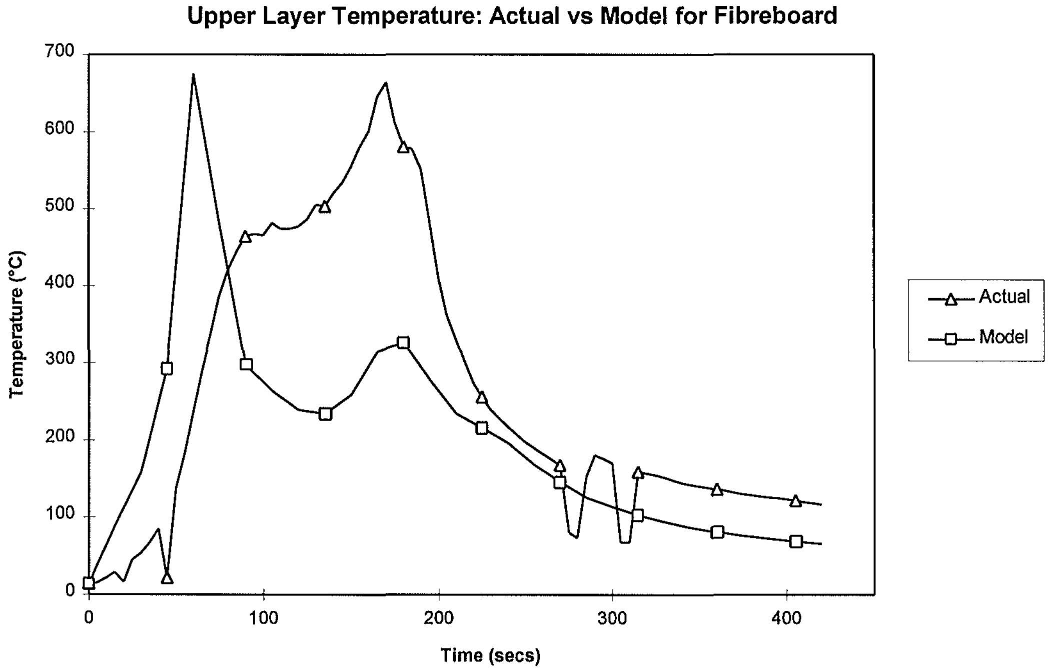

Figure 14: BRANZFIRE vs Actual: UL Temperature for Fibreboard

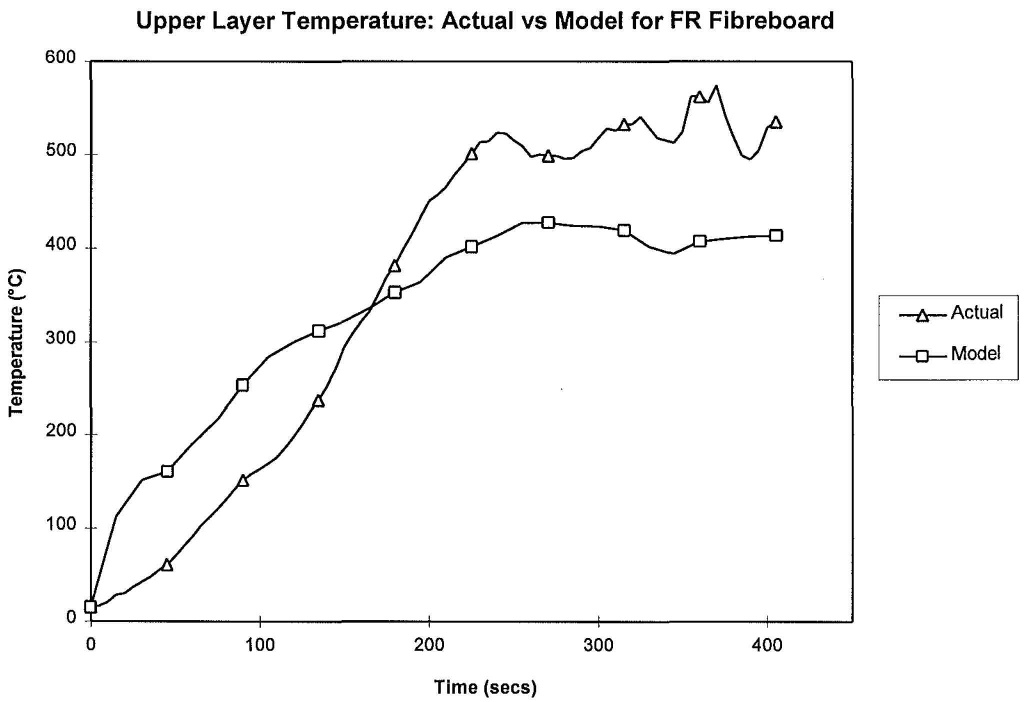

Figure 16: BRANZFIRE vs Actual: UL Temperature for FR Fibreboard

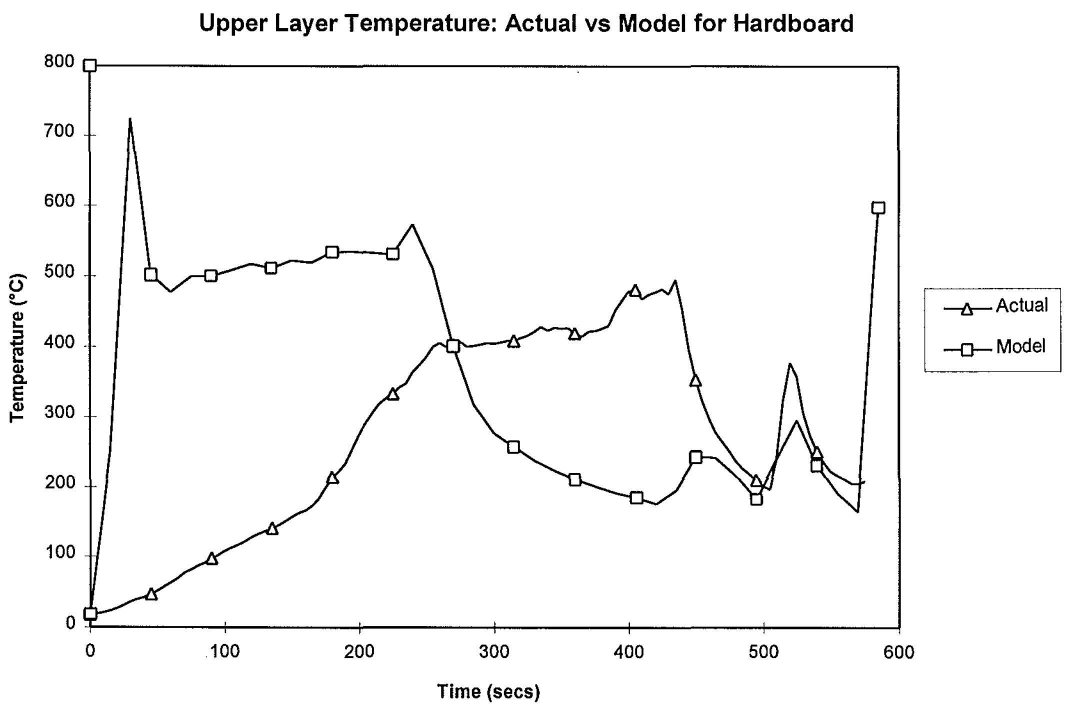

Figure 15: BRANZFIRE vs Actual: UL Temperature for Hardboard

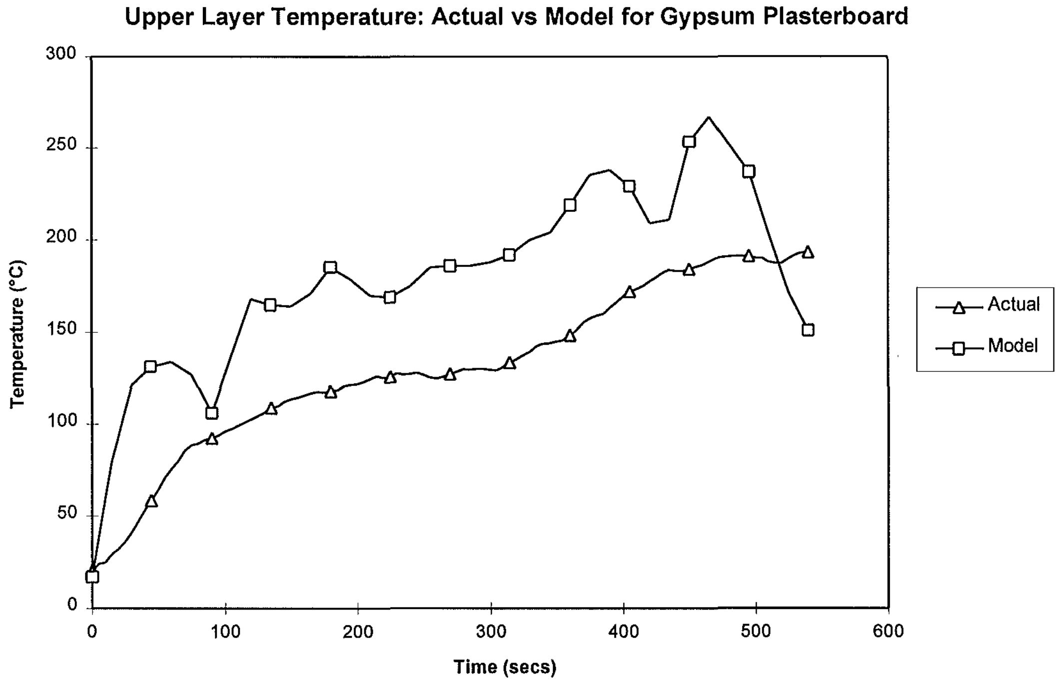

Figure 17: BRANZFIRE vs Actual: UL Temperature for Gypsum Plasterboard

Figure 14 shows that for the Fibreboard the model predicts too rapid a rise in the UL temperature. Peak values are however similar and the decay phase is well modelled from around 215 seconds onward.

With regard to the FR Fibreboard the rise in temperature predicted by the model is again faster than that which was measured, although the shape of the curve is similar. The model in this case under predicts the maximum UL temperature by around 100°C. No reliable experimental decay data was available for the run.

Figure 15 shows that in the case of the Hardboard the UL temperature exceeded 600°C at an early stage, as this is only for a short time flashover is not predicted, a conclusion which is supported by experimental observation. The temperature then drops rapidly to around 500°C, showing a plateau and a drop to around 200°C in the late stages of the simulation. The experimental results show some significant differences in the fact that the temperature rises much more slowly and drops at a time around 180 seconds after the predicted drop. Reasons for this may be in the unpredictable burning of the Hardboard which had a tendency to shatter, creating significant debris when burning before full combustion could take place. This debris was also prone to falling in the fuel pan thus making accurate mass loss and subsequent ignitor HRR measurements extremely difficult.

In the case of the Gypsum Plasterboard, as the material did not readily combust this result is important as it helps to demonstrates the effectiveness of the BRANZFIRE zone model. The model predicts with very good accuracy the shape of the UL Temperature curve although the model over predicts the actual temperatures by around 50°C - 80°C.

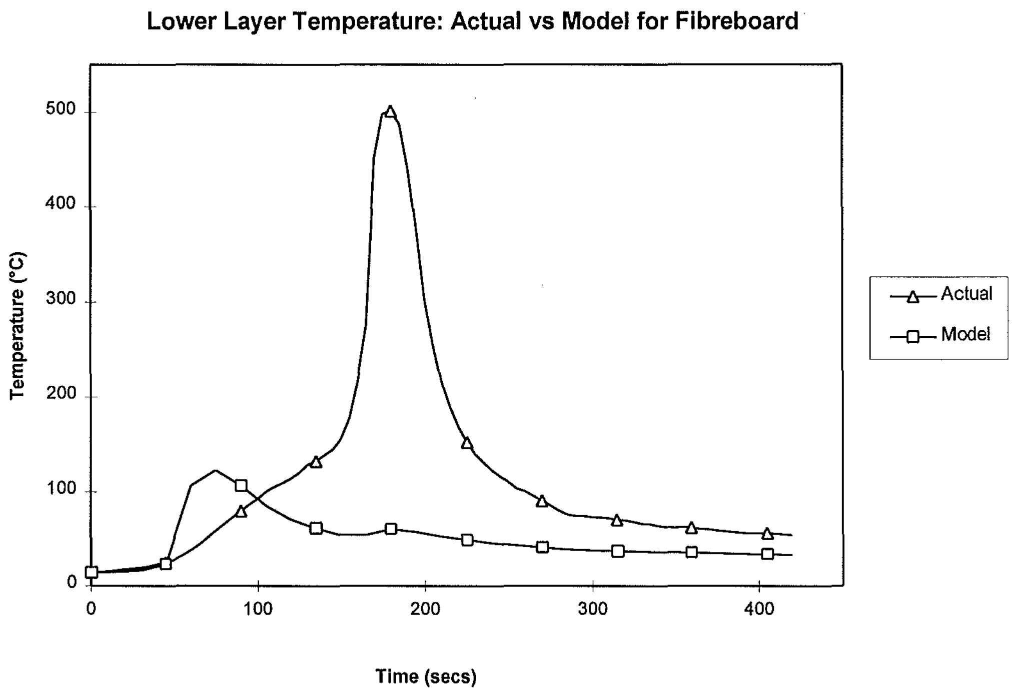

Figure 18: BRANZFIRE vs Actual: LL Temperature for Fibreboard

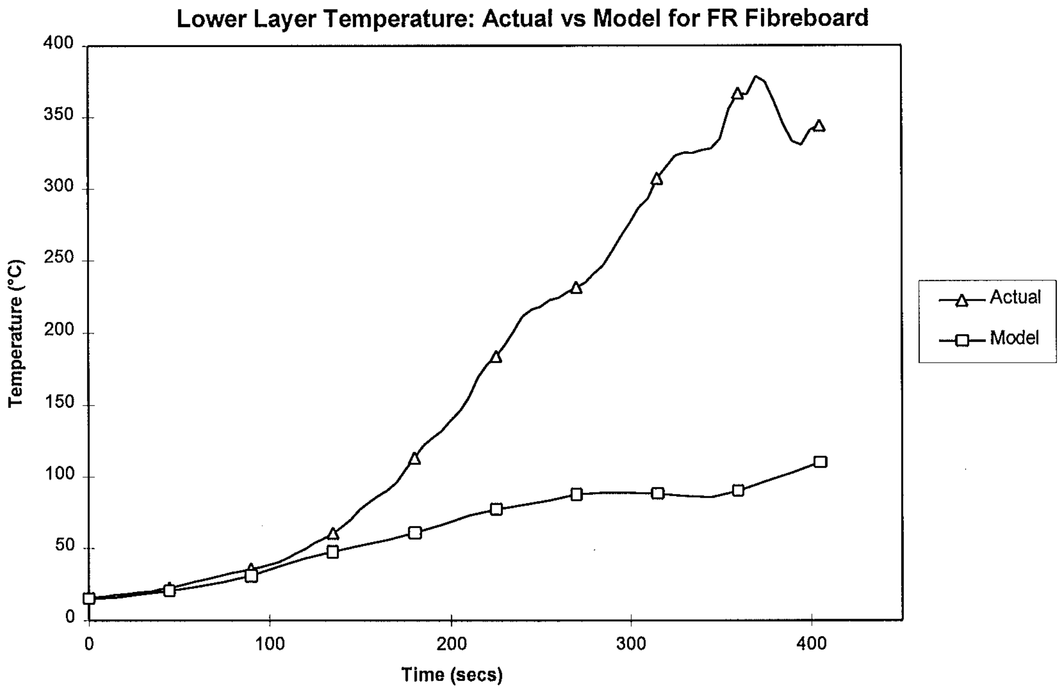

Figure 19: BRANZFIRE vs Actual: LL Temperature for FR Fibreboard

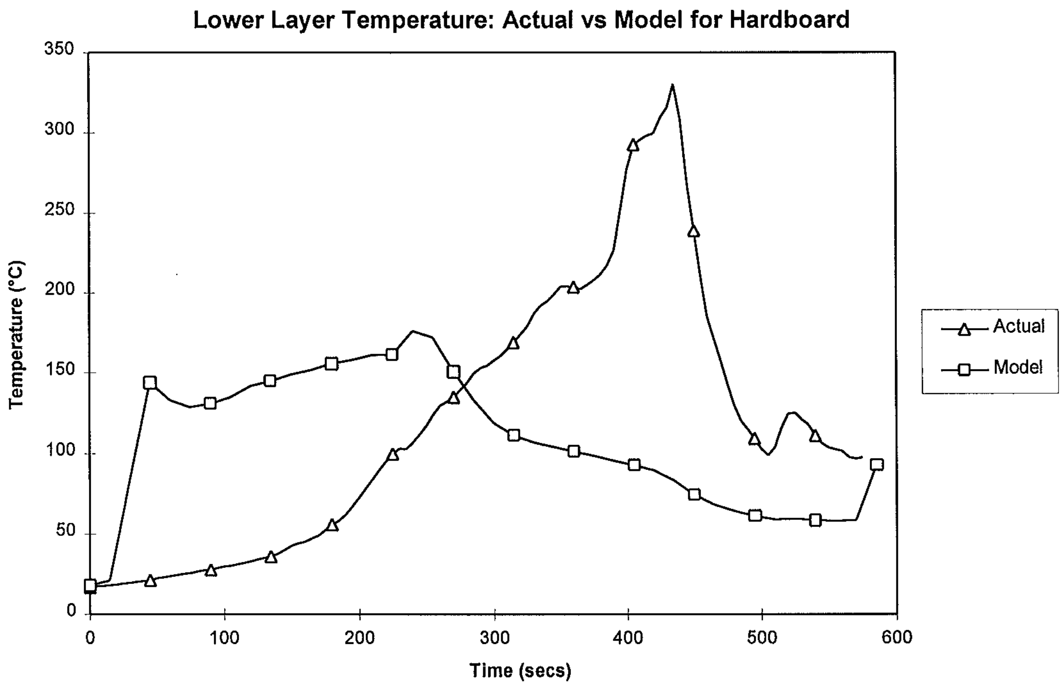

Figure 20: BRANZFIRE vs Actual: LL Temperature for Hardboard

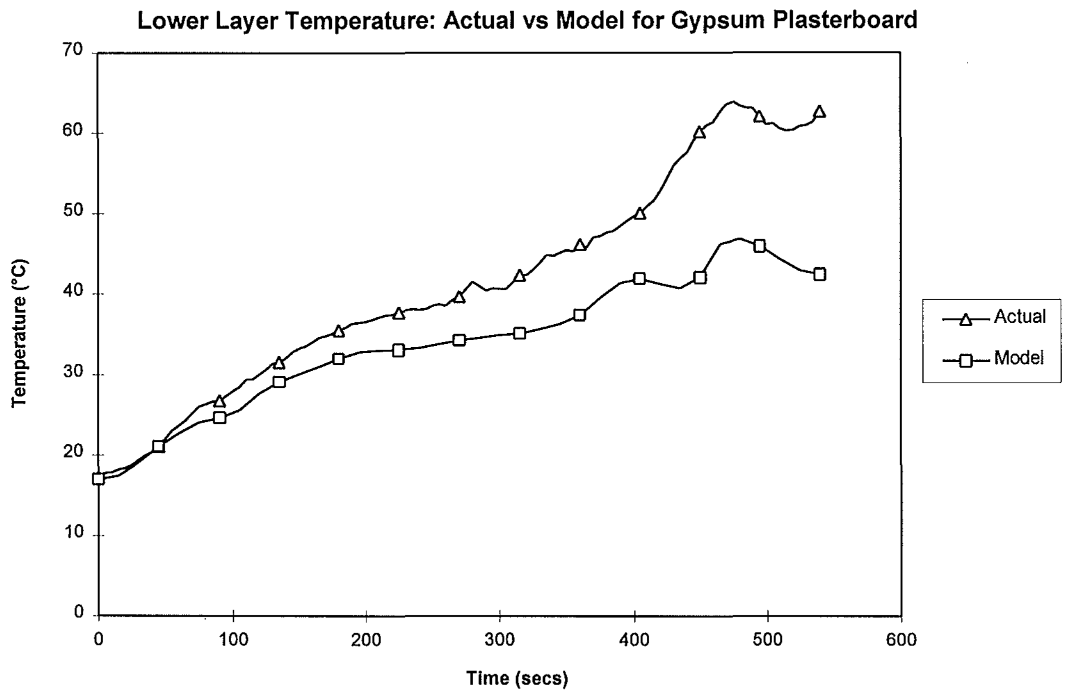

Figure 21: BRANZFIRE vs Actual: LL Temperature for Gypsum Plasterboard

Figure 18 - Figure 21 show very significant under prediction of the LL temperature in terms of all materials, perhaps with exception of the Gypsum Plasterboard. In the case of the Hardboard and Fibreboard the model also fails to predict accurately where the peaks will occur with the predicted peak values resulting from initially rapid rises in temperature.

In considering these phenomena it is necessary to compare where the interface height is at the time when very high compartment lower layer temperatures arise. In the above cases the corresponding interface heights are far below (>0.5m) the sill height of the compartment and the layer could not be physically observed. In this situation it was observed that there was almost nil air flow into the compartment. When the layer dropped just below the sill (<0.25m) significant air flow into the compartment was still observed. Another factor which should be taken into account is the fact that the lowest thermocouple on the tree was located at 0.26m above the floor. Thus the minimum possible interface height as calculated (see Appendix 2) could be 0.26m even though in reality the interface may not have existed with upper layer extending to the floor.

Hence it may be a valid assumption that when the layer drops significantly below the sill height, for example >0.5m below, the interior of the compartment could be considered as one zone at a temperature more representative of the upper layer. If this was to be the case then lower layer temperature data for Fibreboard between 150 and 210 seconds, for FR Fibreboard between 290 and 400 seconds and for Hardboard 370 and 450 seconds may be ignored. This would improve the accuracy of the model greatly. This assumption is backed up by the results for the Gypsum where the interface height drops to only 0.25m below the sill and the resulting LL temperature prediction is far more accurate. This is a problem not faced by the other model which all have sill heights located on the floor by default.

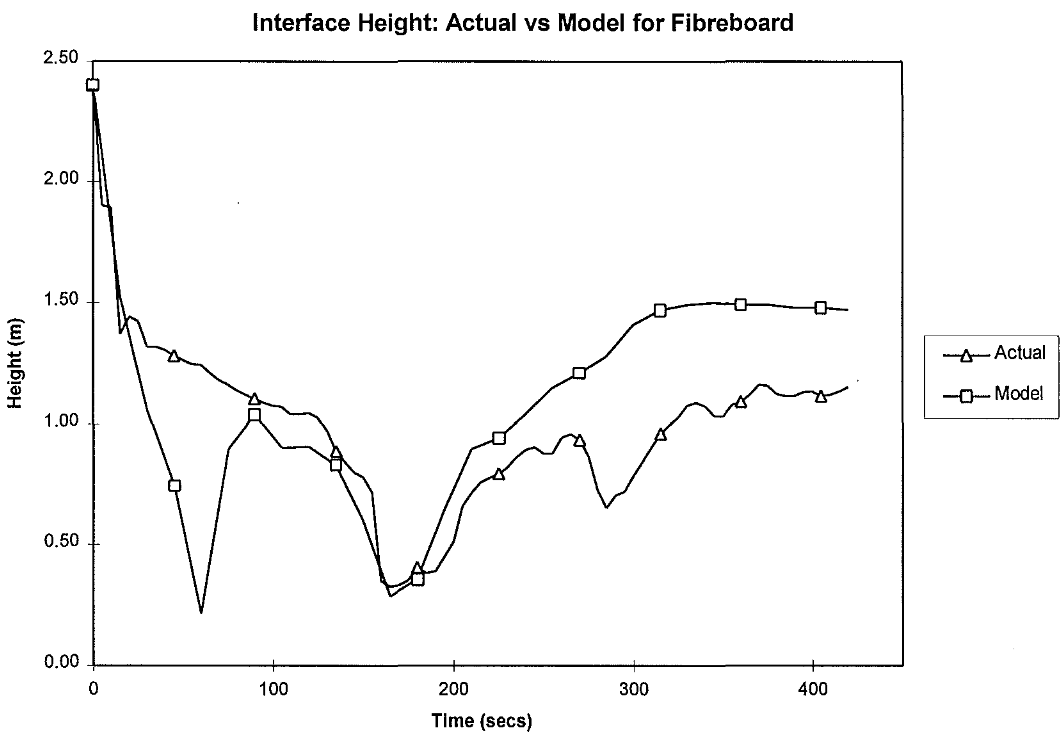

Figure 22: BRANZFIRE vs Actual: Interface Height for Fibreboard

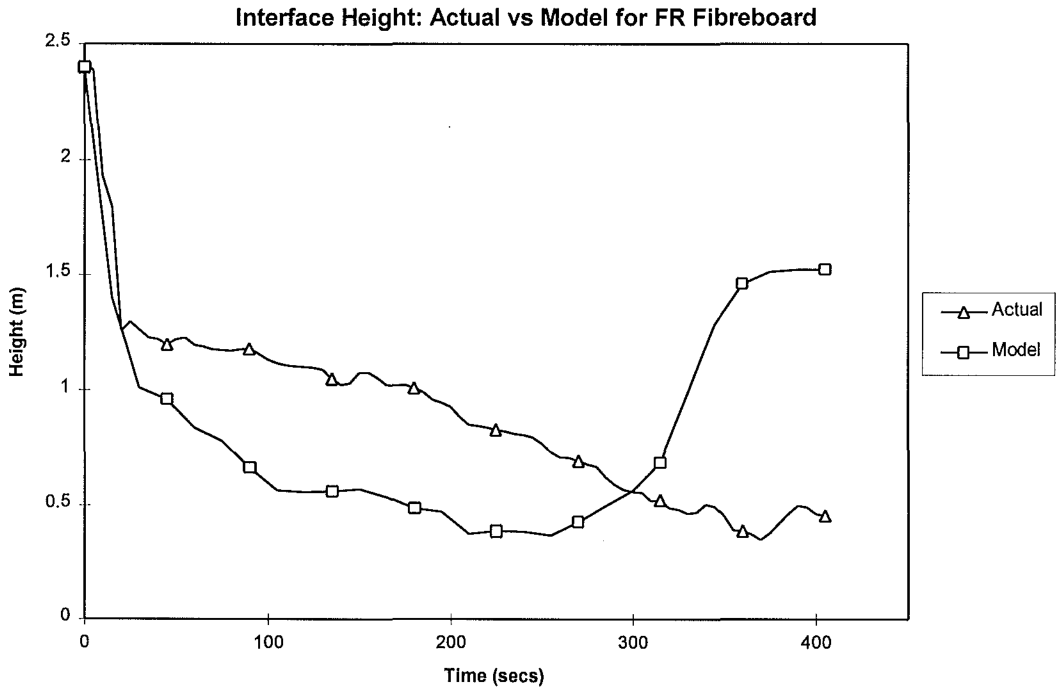

Figure 23: BRANZFIRE vs Actual: Interface Height for FR Fibreboard

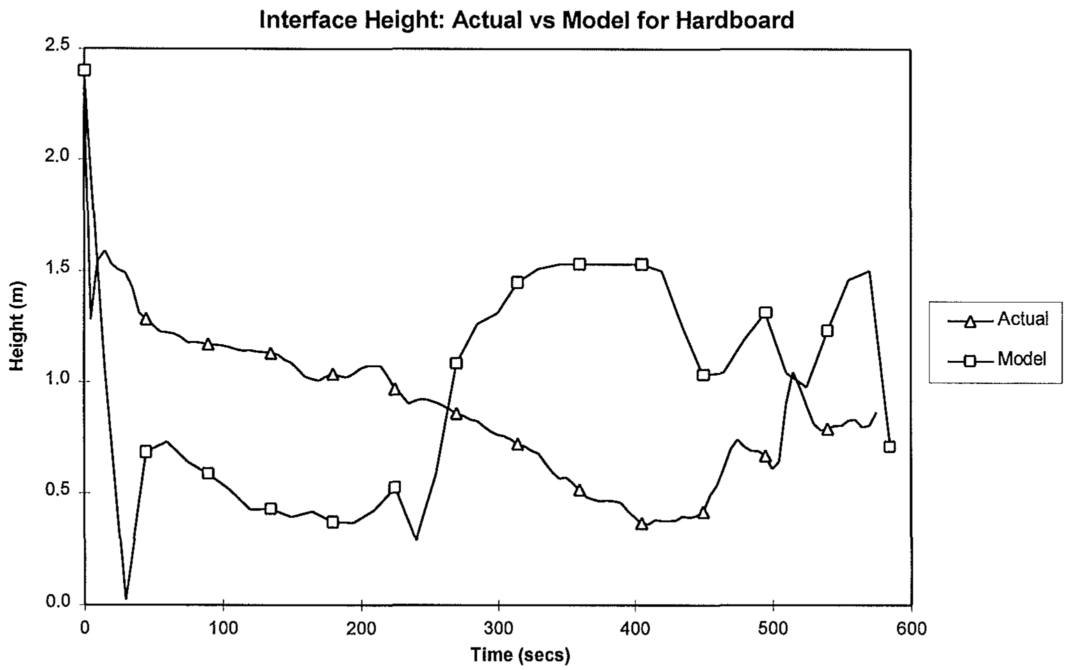

Figure 24: BRANZFIRE vs Actual: Interface Height for Hardboard

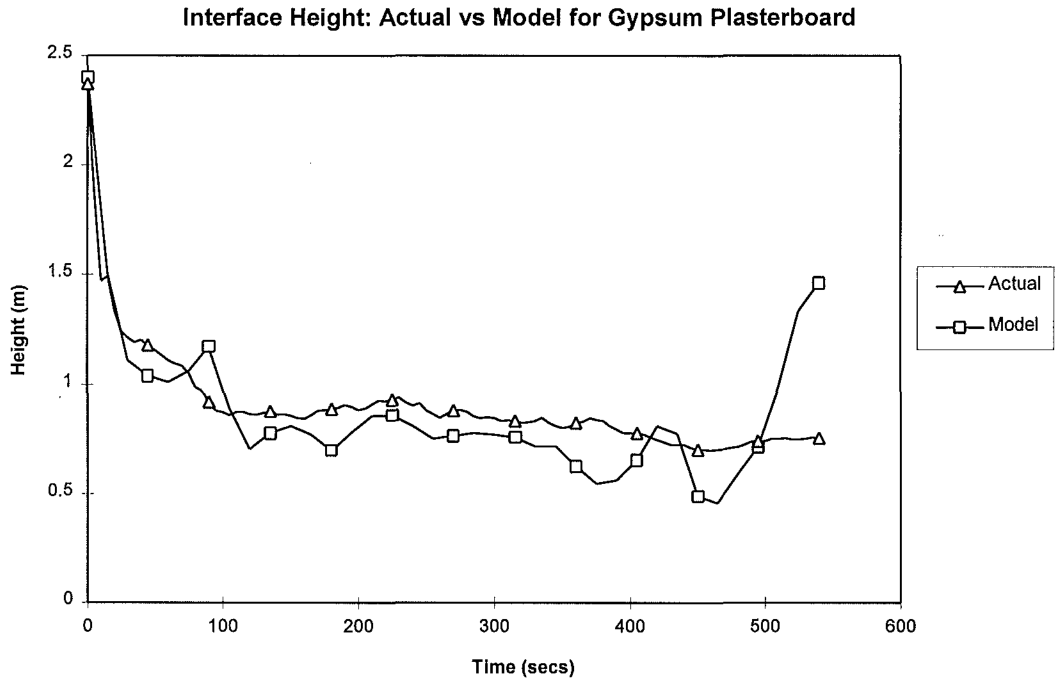

Figure 25: BRANZFIRE vs Actual: Interface Height for Gypsum Plasterboard

As the model seems to predict too rapid a rise in the layer temperatures it also predicts a corresponding rapid decrease in the interface height, where the actual decrease is far more gradual. Again the Hardboard exhibits far different behaviour than that which is predicted. The other materials, especially Fibreboard and the Gypsum Plasterboard are modelled to a good degree of accuracy. The FR Fibreboard shows characteristics consistent with the UL temperature prediction in that where the temperature rises too quickly initially the layer descends too quickly and where the temperature cools to finish below what was found experimentally the layer rises above that measured. The overall accuracy is however still acceptable.

The overall trends exhibited are:

- Prediction of the upper layer temperature too high in the initial stages.

- A corresponding interface height below what was found experimentally.

- A consistent under prediction in the lower layer temperature.

7.1.2. QUINTIERE

Quintiere's model was run for the material properties as specified in Table 4, the results are graphed below.

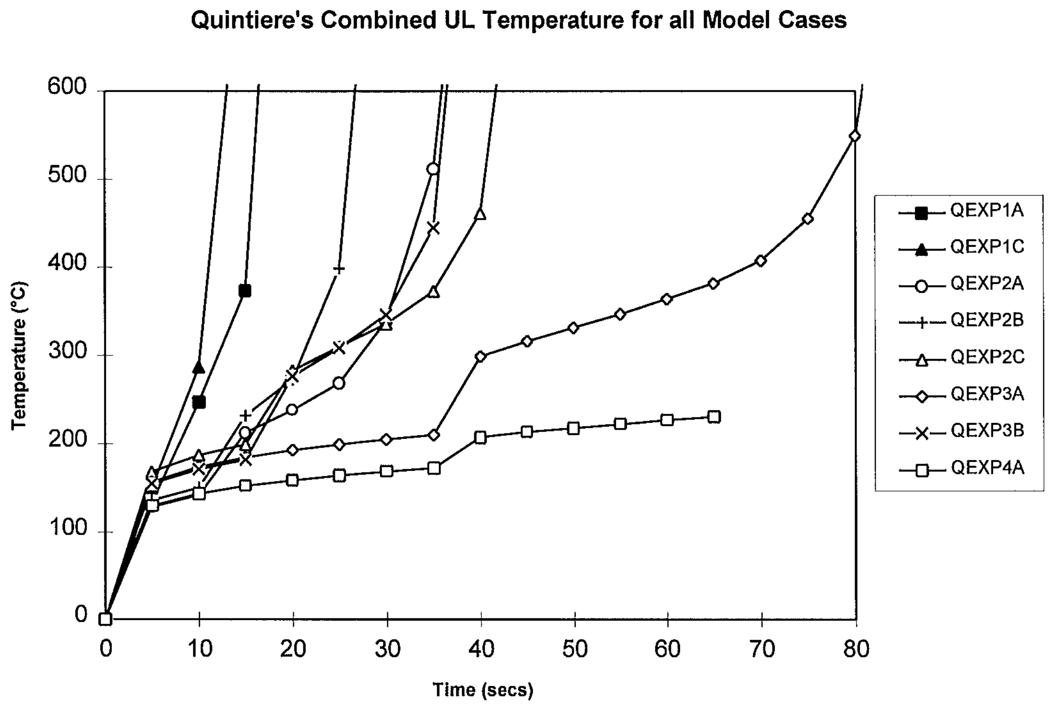

Figure 26: Combined UL Temperatures for all Quintiere's Model Cases

The above graph shows the difference in the specification of the T_{ig} and $k\rho c$ values does have a profound effect on the materials predicted performance. The change between QEXP3A and QEXP3B in terms of time to reach 500°C is in excess of 40 seconds or over 50%, for a 35% change in T_{ig} and a 9% change in $k\rho c$. Similarly the difference between QEXP2B and QEXP2C is approximately 40%.

Quintiere's model assumes flashover occurs when the upper layer temperature reaches 500°C or the HRR from the compartment exceeds 1MW. Thus according to these results flashover will occur with all but the Gypsum Plasterboard lining. As the correlation's applicability does not extend to post-flashover fires the data beyond 500°C may be disregarded.

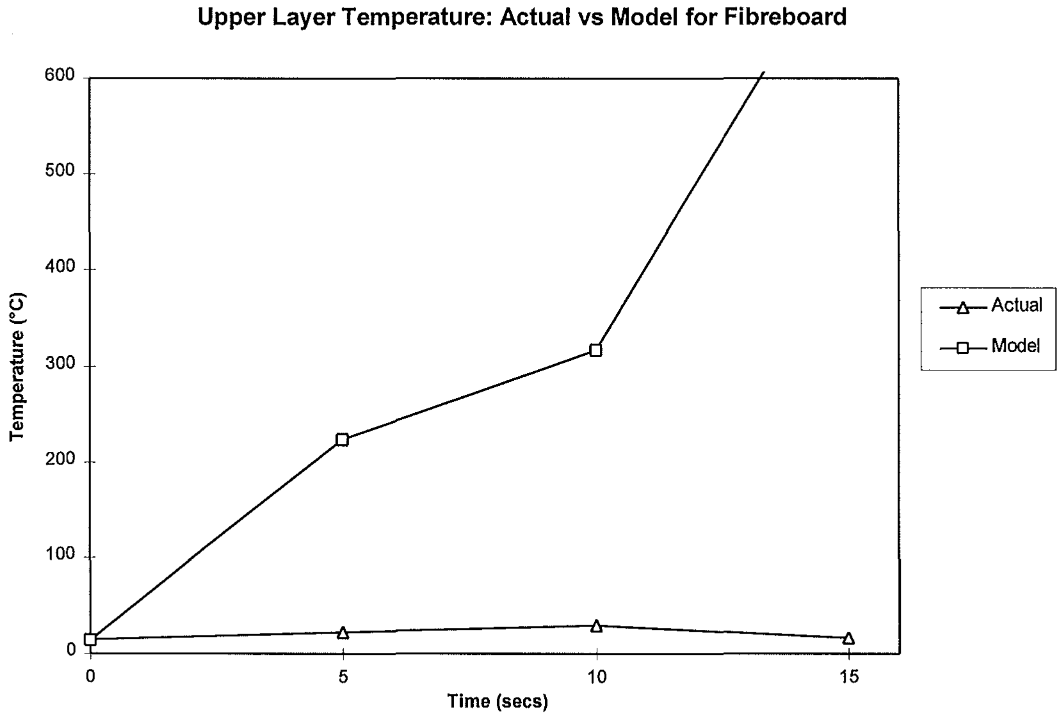

Figure 27: Quintiere's vs Actual: UL Temperature Fibreboard

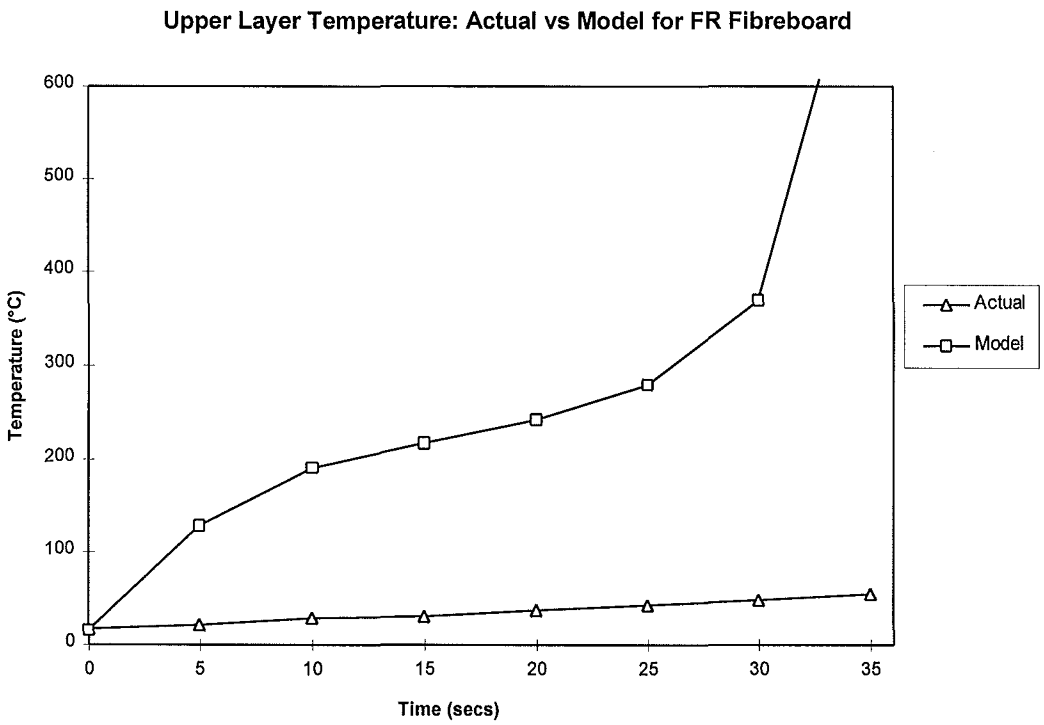

Figure 28: Quintiere's vs Actual: UL Temperature FR Fibreboard

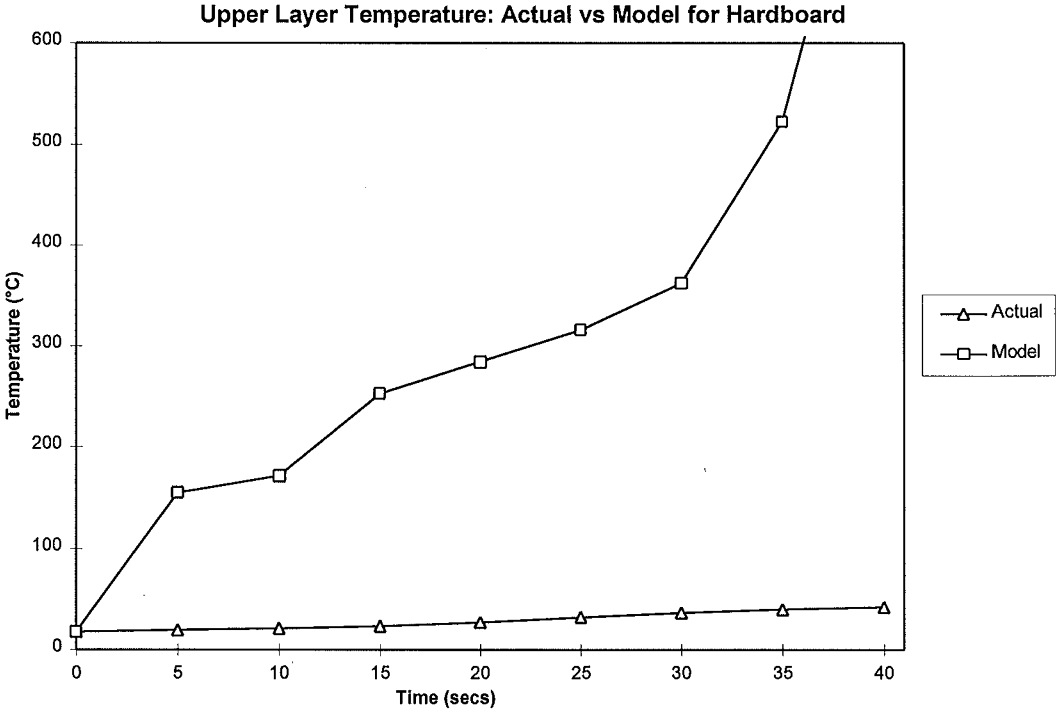

Figure 29: Quintiere's vs Actual: UL Temperature Hardboard

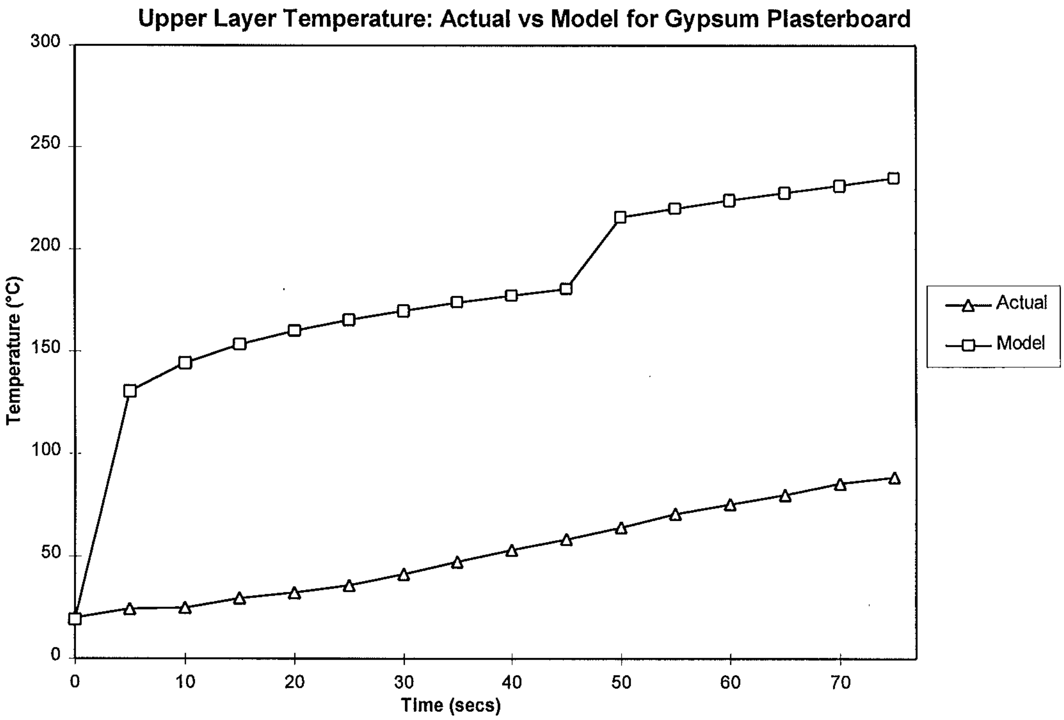

Figure 30: Quintiere's vs Actual: UL Temperature Hardboard

The most obvious point to note from these graphs is the extremely rapid rise in temperature for all materials with the exception of the Gypsum Plasterboard. This rapid rise in temperature means that Quintiere's model under predicts the time to reach 500°C by at least 85%.

Table 5 below summarises the times taken to reach various temperatures in the modelling and in the experiment. It is important to note that in the case of the experimental results 500°C does not indicate flashover.

Material	**Times to Reach Temperatures, Modelled / Actual (seconds)**							
	100°C		**250°C**		**400°C**		**500°C**	
Fibreboard	<1	50	7	60	11	75	12	130
FR Fibreboard	1	65	21	140	31	185	33	225
Hardboard	<1	95	15	195	32	255	32	-
Gypsum Plasterboard	1	110	-*	-	-	-	-	-

*Denotes temperature not reached

Table 5: Comparison of Actual Times to those Predicted by Quintiere to Reach Various Upper Layer Gas Temperatures

Table 5 shows the trend that, excluding the times to reach 100°C, all of the times to the various temperatures are between 83% and 92% less than the actual time to reach that temperature, i.e. the most accurate result still under predicts the time by 83%. In his own research the HRR in the ISO experiments exhibits a far more rapid rise probably due to the burner being a constant HRR.

7.1.3. Karlsson

In a series of papers Karlsson compares results from the various sub-models of his overall model to experimental data using the Swedish and EUREFIC materials. These are the sub-models used for calculating gas temperatures, surface temperatures, heat fluxes and HRR's. The basis for much of Karlsson's work, like Quintiere's, lies in the attempted modelling of the HRR and the onset of flashover in a compartment, thus not a great deal of data is available concerning the gas temperature model. Karlsson's claims that the analytical solutions show good agreement with experimental data for 21 materials are well backed up by the published results. Table 6 below is a table of Karlsson's results for 21 full scale room-corner fire experiments using the Swedish and EUREFIC materials.

It is important to note that data taken here has been read directly from graphs so is itself accurate to +/- 5 seconds. Also, Karlsson derives his own material property data for the Swedish materials, as such there are small differences in $k\rho c$ and T_{ig} values between his research and the assembled results of Quintiere et al.[37]. Karlsson's parameters may be found in his PhD.. thesis[1].

One key point to note when considering the data in Table 6 is the burner program for the experiments. Karlsson's experiments are consistent with ISO 9705 in that it steps from 100 kW to 300 kW at 600 seconds if flashover has not occurred by that stage. Thus a time to reach any temperature in excess of 600 seconds does not represent a gradual rise instead it shows that the material readily combusted only after the step up in HRR.

It is apparent that over most of the materials Karlsson's model is under predicting the time to reach the various temperatures. At 500°C however there are 8 of the 21 materials which have the time over predicted.

Of the materials in Table 6, of most interest are the materials s1 and s4 which correspond to the Fibreboard and the Gypsum Plasterboard used in the BRANZ experimental program.

Material	Times to Reach Temperatures, Modelled / Actual (seconds)					
	200°C		400°C		500°C	
s1	12	25	35	40	42	50
s2	40	60	95	105	112	-*
s3	42	57	100	110	120	150
s4	50	50	605	615	640	-
s5	10	40	50	610	70	615
s6	35	20	605	610	620	615
s7	40	55	100	105	115	615
s8	15	25	25	38	30	55
s9	45	100	135	400	170	460
s11	3	4	6	9	9	11
s12	40	40	105	80	130	110
s13	40	50	130	105	150	135
e1	90	50	605	610	670	615
e2	55	50	130	90	140	115
e3	60	40	120	90	620	110
e4	50	100	605	610	610	-
e5	80	130	605	690	660	-
e7	3	15	605	40	610	90
e9	50	95	135	180	150	195
e10	30	50	605	615	620	660
e11	55	40	65	65	125	75

*Denotes temperature not reached

Table 6: Comparison of Actual Times to those Predicted by Karlsson to Reach Various Upper Layer Gas Temperatures

In the case of the Gypsum Plasterboard the upper layer temperature reached 200°C after 50 seconds in Karlsson's experiment and then plateaus at around 210°C until the step up to 300 kW. In the research carried out at BRANZ 200°C was not reached with peak value being 191°C at 490 seconds after a gradual rise at which stage it plateaus. Modelling in BRANZFIRE with the ISO 9705 burner, 200°C is only reached after the step up to 300 kW with 400°C not reached. Quintiere's model does not predict 200°C prior to 600 seconds but instead plateaus at around 130°C. Table 7 summarises the comparison between the three models and two experiments.

Model	**Time to Reach Temperatures (seconds)**		
	200°C	**400°C**	**500°C**
BRANZ Experiment	-*	-	-
Karlsson's Experiment	50	615	-
BRANZFIRE (ISO Burner)	606	-	-
Quintiere (100 kW)	DNA**	DNA	642[iii]
Karlsson (ISO Burner)	50	605	640

* Denotes temperature not reached

** Denotes data not available

Table 7: Comparison of Predicted and Actual Times to reach Various Upper Layer Gas Temperatures for Gypsum Plasterboard

As can be seen BRANZFIRE and Quintiere predict vastly different results than those predicted by Karlsson. However there are also vast differences in the results of the two similar experiments. These are due to the small differences in the experimental setup, for example the difference in HRR supplied from the burner. In the BRANZ experimental program the HRR from the pan in Experiment 4 fluctuated between 150 and 20 kW being on average 97 kW, lower than the relatively steady 100 kW in Karlsson's work. Also the ISO compartment has a far larger vent (2.0 m x 0.8 m) which has a marked effect in the zone model calculations.

Modelling the Fibreboard produces more comparable results as all scenarios produce an upper layer gas temperature of in excess of 500°C prior to the 600 second step in HRR. Accordingly Table 8 below shows the comparison between the models and experiments.

[iii] this value was not independently modelled but is taken as the time to reach 1 MW in Quintiere's experiments[37]. No.times to reach 200°C or 400°C were available.

Model	Time to Reach Temperatures (seconds)		
	200°C	400°C	500°C
BRANZ Experiment	50	75	130
Karlsson's Experiment	25	40	50
BRANZFIRE (ISO Burner)	32	45	48
Quintiere (100 kW)	26	39	41
Karlsson (ISO Burner)	12	35	42

Table 8: Comparison of Predicted and Actual Times to reach Various Upper Layer Gas Temperatures for Fibreboard

BRANZFIRE and Quintiere show the best agreement to the experimental result of Karlsson, with Quintiere being within 1 second accuracy in the prediction of time to 200°C and 400°C. Karlsson under predicts the times consistently indicating that the pyrolysising area used by Quintiere to calculate the total HRR may be more accurate than that of Karlsson as the temperature correlation used is the same. Again the difference between two relatively similar experiments is very significant.

7.1.4. Janssens

Janssens model is similar in principle to those of Karlsson and Quintiere in that it uses the same upper layer temperature correlation (Equation 9). It is also more concerned with predicting the HRR in the compartment in order to predict the onset of flashover than the other tenability conditions in the room. The differences in the model from that of Quintiere lie in the mathematical simplifications Janssens makes by altering the pyrolysis area, and the calculation of heat fluxes as opposed to the assumptions made by Quintiere (as explained in Chapter 3). A comparison of published results[6,13] reveals that Quintiere's model seems to be more accurate given the materials tested. No reliable upper layer temperature data was available to compare this model.

7.2. CONSIDERATION OF INPUT REQUIRED

BRANZFIRE can operate without the explicit input of thermal inertia and ignition temperature data. However, as is shown in Appendix 3, the time to ignition measured in the cone calorimeter which is required for at least three irradiances can lead to significant changes in these parameters. Added to this the assumption which Janssens method makes, that the material behaves as a thermally thick solid may not be appropriate for some materials and can lead to vastly different results than those quoted from analysis of LIFT apparatus data. In using the LIFT apparatus however data is still variable[32] for the same materials i.e. for Gypsum Plasterboard (Swedish material s4), Karlsson[1] quotes values of 0.546 $kW^2s/m^4/K^2$ and 503°C whilst Quintiere[2] has published 0.450 $kW^2s/m^4/K^2$ and 565°C and Sundström[20] reports 0.515 $kW^2s/m^4/K^2$ and 469°C. Despite these differences the preferred method of obtaining these parameters would be though the use of the LIFT apparatus.

As BRANZFIRE incorporates a zone model additional input is required when compared to the other models. The thermal properties of the materials which line the walls are required, this is part of the zone model and is used for heat transfer calculations. Vent geometry including sill height is required with the provision for more than one vent to be defined. Vent opening times can also be entered.

Quintiere's model requires the explicit statement of the $k\rho c$ and T_{ig} values. It also requires the statement of a single constant HRR, which in the case of the BRANZ experiments needed to be an average value. Aside form these considerations the input to Quintiere's model can be rather cumbersome as there are a lack of default values, thus of the 32 variables all but seven must be directly specified. When examining the variables also, it becomes apparent that some are directly related to others and could be calculated within the model however this is not done and they are explicitly required. Appendix 5 contains an explanation of the complete input required in Quintiere's model.

Janssens is a complete model for ISO 9705 compliant tests, thus it requires similar data to Quintiere's but does not allow the changing of the vent size, compartment size and limits the burner routine to ASTM or Nordic standards (see Table 1). It does not require as much input as Quintiere's as some data is calculated within the model.

7.3. Consideration of User Interface

In terms of a user interface and the subsequent user friendliness or otherwise to fire engineers at all levels, BRANZFIRE rates considerably better than the other models tested. BRANZFIRE is run under a Windows interface making it easier to use than the other MS-DOS type interfaces. The inputs to the program are easily viewed and help is available. Most default values may be changed with a minimum of key strokes allowing wide scope for analysis of fire situations.

By contrast the other models are MS-DOS based and are compiled from FORTRAN or BASIC programming languages. The ease with which data can be changed is somewhat limited. Karlsson's model for example was unable to be run at all as the input stage of the program is somewhat indecipherable. Values are asked for simultaneously with no mention of the units to be entered or the way in which to separate the variables. No help or accompanying instruction is available. A cone data file is asked for at which stage it is possible to enter the data files for some of the Swedish fire test materials and the EUREFIC materials however always at this point the program gives an error and will not proceed. As no code listing was available, pinpointing the source of this error is impossible.

Quintiere's model was supplied with a list of the input variables required, with accompanying units and a reference to papers in which these variables were more fully explained. Input was done directly into an ASCII text file so was relatively easy with the explanation of variables.

As explained above Janssens has a minimal user input such that parameters like HRR and vent size must be changed within the code itself

This contrasting MS-DOS based approach whilst not presenting the task of analysis as impossible do tend to discourage the use of the programs by anyone other than the already knowledgeable. This may be seen as advantageous in some circumstances as it may prevent or discourage those with little knowledge using it. In saying this however I believe it is preferable to have a user friendly informative program with appropriate on-line help which can be used readily by many. Those software packages which are difficult to understand and poorly presented put people at risk by giving greater opportunity to those who have limited knowledge unwittingly inputting incorrect data it in order to get the "right" answer for their client.

8. APPRAISAL

It has been shown that BRANZFIRE models the BRANZ experimental room-corner fires with a good level of accuracy, and is certainly more accurate than the other models. Although it has the tendency to over predict the rate of fire growth this is to a far lesser extent than Quintiere, Karlsson and what would be expected from Janssens. In any case an over prediction is preferable to under prediction and may be looked upon favourably as a conservative approach.

It is expected that no model be able to exactly predict the nature or growth of every given fire as pointed out by Nelson et al.

> *"In comparing results the user must understand that the reality of accidental fire is more varied and complex than can be exactly described by any existing collection of equations or exactly measured in any test. Some deviation should always be expected. The deviation from reality may occur in the predictions by the model. In the measurements undertaken in the tests, or most likely, a combination of both."*[26]

Quintiere's is the most complex of the models in the way in which it attempts to model the pyrolysis area from a corner burner and subsequent pyrolysis of the wall and ceiling lining material. Judging by the published results this would seem to be appropriate and the best way in which to approach the problem, as the predicted HRR and upper layer gas temperature seems to be more accurate than Karlsson and HRR more accurate than Janssens. Karlsson's model however also shows good agreement with his observed experimental data and as such Wade incorporates both flame spread models in BRANZFIRE .

The effectiveness of any model may be judged on the output produced however this is only as good as the data which is input. All of the models require T_{ig} and $k\rho c$

values, these may be evaluated from cone calorimeter data or measured directly using LIFT apparatus. If using Janssens method to evaluate the parameters from cone calorimeter data the values will not be valid for materials not displaying thermally thick characteristics. The values are also extremely sensitive to small changes in the input cone calorimeter data. BRANZFIRE allows the option to provide a cone calorimeter data file without the explicit statement of the T_{ig} and $k\rho c$ values and computes them using this method. This should be used only if data does not already exist for the material being examined.

In his paper[6] Quintiere claims that his model underestimates the time to flashover for the homogeneous relatively thick materials tested but is accurate to within 50% of the experimental values. This is shown not to be the case with the BRANZ experimental program where the HRR is not constant, but must approximated as such, and the vent sill height is above the floor level. The accuracy of the model in this case is poor proving that this approximation is very significant in the model results. Quintiere explains however:

> *"The simulation model offers (1) an illustration of how to use fire property data for prediction of fire growth scenarios, (2) a basis for elucidating needed research for improving fire growth models, and (3) a preliminary basis for assessing the fire hazard of materials."*[6]

On the first two counts the model performs well if used in its prescribed manner i.e. as a research tool to model a very controlled fire growth situation. With regards to the third the model should be viewed as inferior to BRANZFIRE as its results, although conservative, are far less accurate. BRANZFIRE also offers much needed adaptability in the choice of real fire scenarios due principally to the ability to input any HRR curve into the model and the zone model which can account for many vents, this is important in the initial assessment of fire hazard. This is to be expected as BRANZFIRE is designed as more of a fire engineering design tool as opposed to the other models which are, at present, very much research based. This is in keeping with the aims of Wade whose brief for the purpose of BRANZFIRE was to allow the hazard or threat to life safety in a building to be assesed.[3] She goes on to outline the importance of developing a user friendly program.

> *"Emphasis has been placed here on developing a user-friendly interface for BRANZFIRE based on the Microsoft Windows environment, thus making it more accessible to fire designers and fire protection engineers as well as other researchers."*[3]

BRANZFIRE therefore is the closest to becoming a reasonable tool with which fires can be modelled with some degree of accuracy, and the only one of the four which has the capability to examine life safety and tenability as it calculates gas concentrations, visibility FED's and the like. In saying this it is essential not to lose sight of the fact that BRANZFIRE is only currently available in a beta release and as such there is a great deal more experimental comparison work which needs to be done to further validate the model. The others are all adequate models for HRR prediction in a very controlled environment.

All of the models consist of sub-models of varying degrees of sophistication, this feature means that as each sub-model is improved upon so the overall model should improve. The sub-models which are included in BRANZFIRE are no exception. Any advance in the flame spread models of Karlsson and Quintiere should be incorporated to improve BRANZFIRE. Similarly advances made by the likes of Delichatsios and those refining McCaffrey's plume correlation could be incorporated into the model. This makes BRANZFIRE an evolving tool which can capitalise on the advances of any of the other researchers.

At present research is still continuing in the field of flame spread models with Janssens et al. active in the field as part of the US-Slovak Science and Technology Program. Quintiere also appears to be further investigating his model while Wade continues to refine her model at BRANZ. Judging by the comparative lack of recently published material Karlsson appears to have curtailed his research somewhat, although testing of the Swedish and EUREFIC materials in Scandinavia still continues.

When considering the processing time of each model there are appreciable differences. A typical BRANZFIRE model running on a 50 MHz 486 took, on average, 400 seconds, whilst both Quintiere an Janssens were able to complete the model in less than 5 seconds. On a 133 MHz Pentium, more representative of todays typical office technology, BRANZFIRE's run-time fell to 120 seconds. Although this difference is large, time saving features are incorporated in BRANZFIRE in the ease with which output data may be produced and manipulated. Such output can be seen in Appendix 4, this is available after running a simulation with three keystrokes, no other model has this capability.

9. CONCLUSIONS

Without having working models from each of the researchers it is difficult to compare the models. The model of Karlsson supplied was indecipherable and would not run correctly, Janssens however would run but the results did not reflect those published. Therefore comparison for these models was made on the basis of results published.

The models of Quintiere, Karlsson and Janssens were only available for comparison to BRANZFIRE on the basis of an upper layer gas temperature. This is because none of the aforementioned models incorporate a zone model with which to predict lower layer temperature or interface height.

Within the BRANZFIRE model it was found that the flame spread model of Quintiere more accurately described the decay of the fire and as such was used in subsequent simulations. BRANZFIRE was found to predict the experimental data to a good level of accuracy for all materials with the exception of the Hardboard. This may be attributed to the way in which the Hardboard shattered when burning and filled the fuel pan making accurate evaluation of the HRR supplied from the pan impossible. The trend exhibited by BRANZFIRE was to predict too rapid a rise in UL temperature and a corresponding too rapid fall in the interface height, LL temperature was consistently over predicted. In this case, at low interface heights the applicability of a two layer zone model is questioned.

The model of Quintiere over predicted the upper layer temperature in all cases by a considerable amount. This is not reflected in his own published results so is caused by differences in the experimental program, principally the approximation of the actual HRR supplied by the ignitor to the lining as a constant, as is required in his model. This outlined the lack of adaptability in this model to assess "real" fire hazard.

An attempt was made to model the experimental data published by Karlsson with BRANZFIRE and Quintiere's model. This revealed that in the case of this more controlled (ISO 9705) environment BRANZFIRE was still able to model the results to a degree of accuracy comparable to that of Quintiere and Karlsson for the two materials modelled. This result, coupled with those of the modelling of the BRANZ experiments, would refute Quintiere and indicate that the integration of a flame spread and a zone model into a single model is a valid approach to the problem of successfully modelling a room-corner fire.

Significant differences in the modelling were found to exist with varying values of the key material parameters, namely T_{ig} and $k\rho c$. This is a cause for concern as the principle method available in New Zealand for evaluating theses parameters is through analysis of cone calorimeter data using Janssens method. A sensitivity analysis of this method found that $k\rho c$ could vary as much as 25% with as little as a 5% variation in the observed time to ignition at 75 kW/m^2 in the cone calorimeter. This calls into question the applicability of Janssens method in certain circumstances. Evaluation of these parameters using the LIFT apparatus was found to be preferable.

A major difference between the model was the way in which the heat flux from the pyrolysis area to the wall and ceiling were evaluated. Data from heat flux meters during the experiments prove to be inconclusive so the default values for each model were used.

In terms of user interface BRANZFIRE was far more user friendly than the other models. It also demonstrated enormous adaptability and was thought to be a well designed fire engineering tool. Quintiere's, Karlsson's and Janssens' models are far less adaptable and are useful only in a research environment in order to predict flame spread in ISO 9705 compliant experiments.

9.1. RECOMMENDATIONS

Although BRANZFIRE demonstrated an ability to predict the full scale room-corner experiments with good accuracy it is thought that a great deal of further experimental work to validate the model is still necessary. It is thought that the facilities at BRANZ are acceptable for this purpose however it is also important that complete raw data from other room-corner experiments around the world be acquired and attempts made to model these. It is important that modelling take place for a variety of fuel sources, for example liquid fuel burners, gas burners and furniture. The successful modelling of the latter would represent a significant step in the assessment of fire hazard in reality. The purpose of this would be to verify the adaptability which is central to the success of BRANZFIRE as a design tool.

In order to improve all of the models efforts must be made to investigate and improve the sub-models from which they are comprised. With increased computing power available it may become appropriate to modify or eliminate some assumptions which are made to simplify mathematical solutions to problems within these sub-models. Having improved these it is essential that they be made available for incorporation into larger models. Further research would also be of interest in the applicability of the two layer zone model theory where the interface height drops significantly below the sill height in a compartment with a single window type vent. In the BRANZFIRE model this may contribute to the significant over prediction of the lower layer temperature in some cases.

As far as input to all the models is concerned it is seen as important that an investigation be carried out into the applicability of Janssens method to calculate the parameters $k\rho c$ and T_{ig} for certain materials. For materials where this method is found to be deficient data must be obtained directly using the LIFT apparatus.

10. References

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APPENDICIES

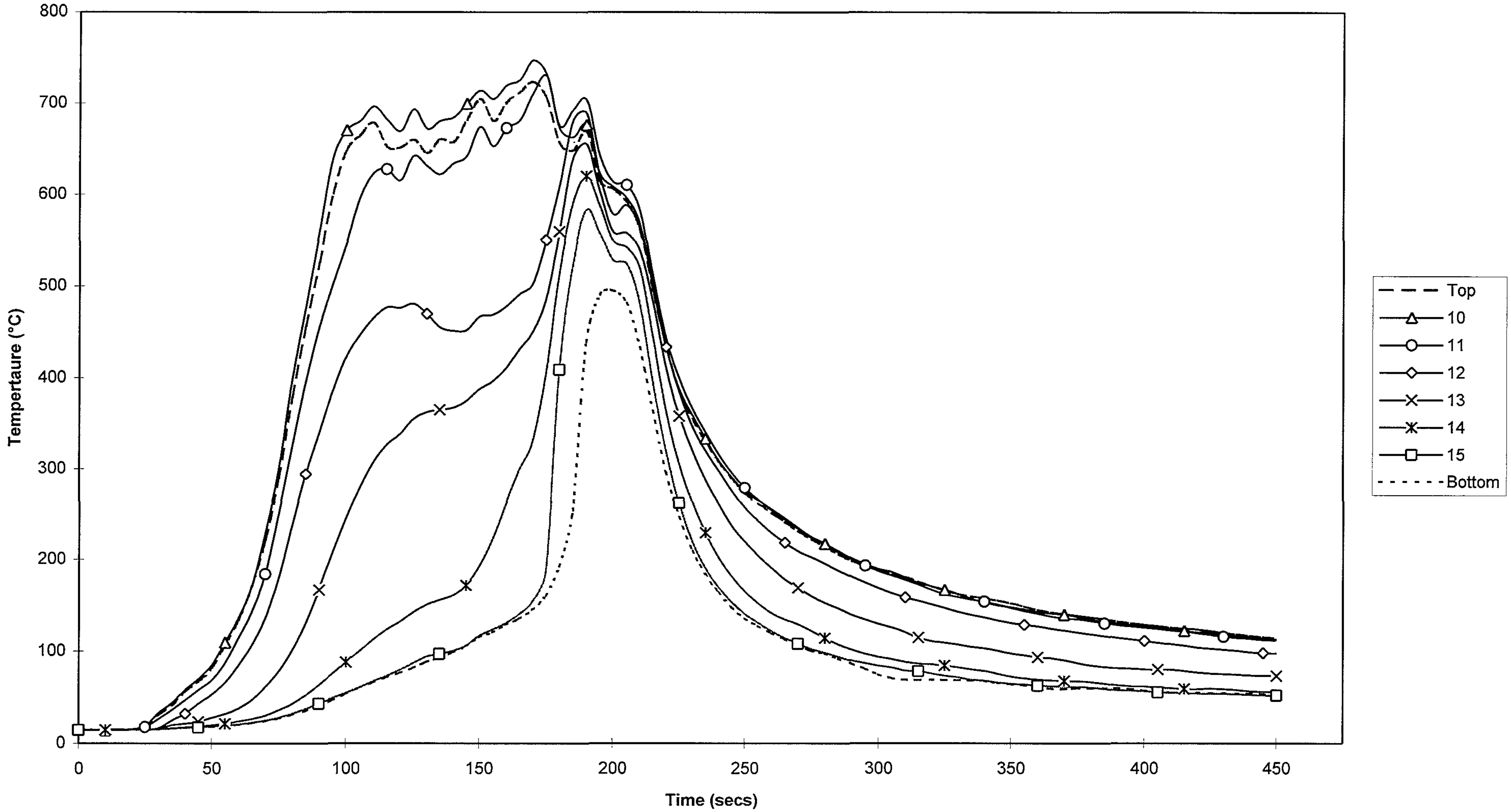
A1. APPENDIX 1: RAW EXPERIMENTAL DATA

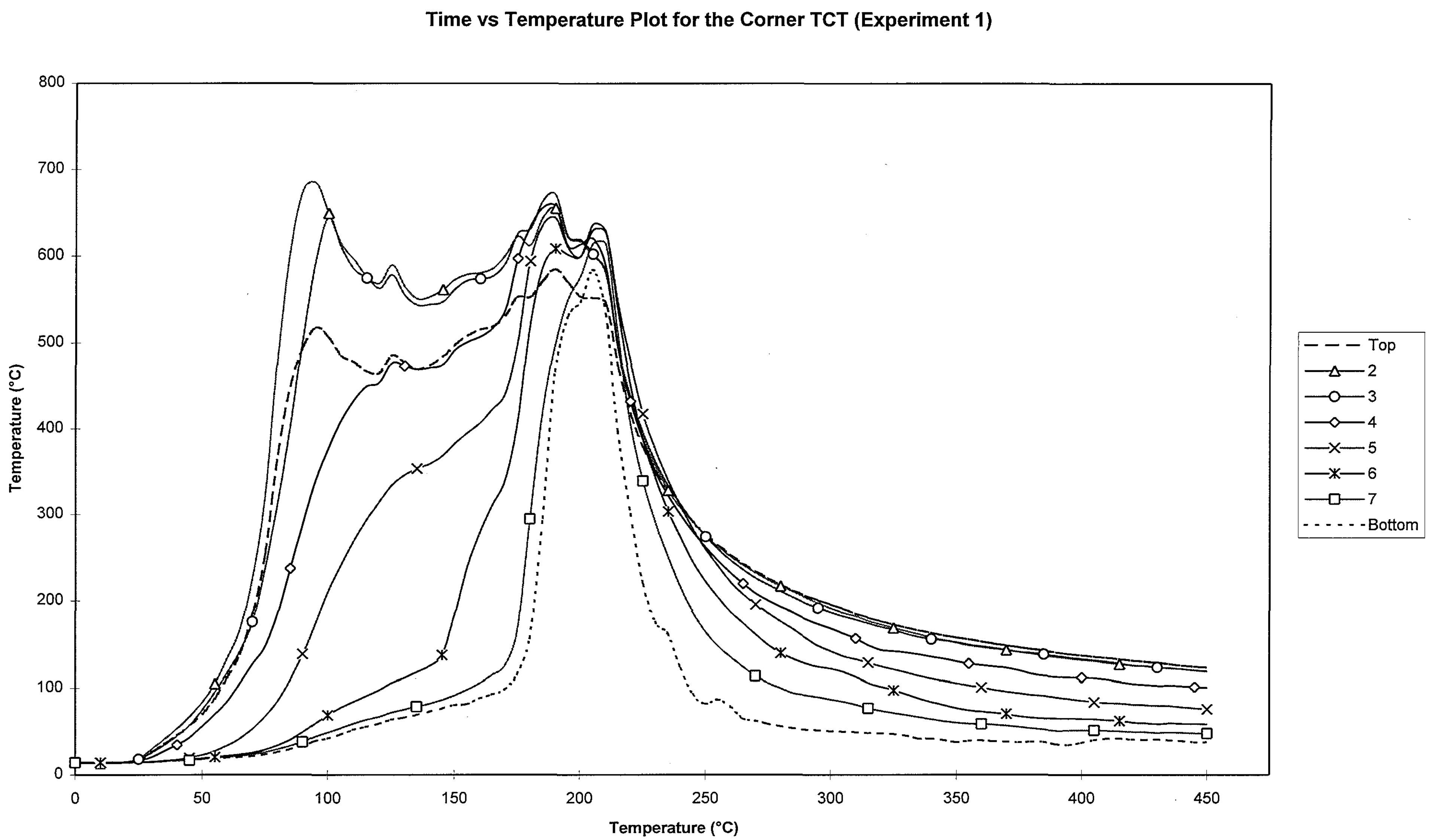
The following graphs represent the data as logged at the time of each experiment. The termination time of each of these graphs corresponds roughly to the time at which reliable data became no longer available, for example when a thermocouple tree collapsed, or too much debris fell into the pan.

The legend entries correspond to the individual thermocouple data logging channels and are numbered in ascending order from the roof down, i.e. the top thermocouple is labelled 'top' and the next below this will be numbered '2' or '10' or '58' and so forth for the various TCT's.

The heat flux readings are given with the meter closest to the burner labelled 'Bottom', this meter was approximately 650mm above the burner, with the meter labelled 'Top' being around 1200mm from the burner.

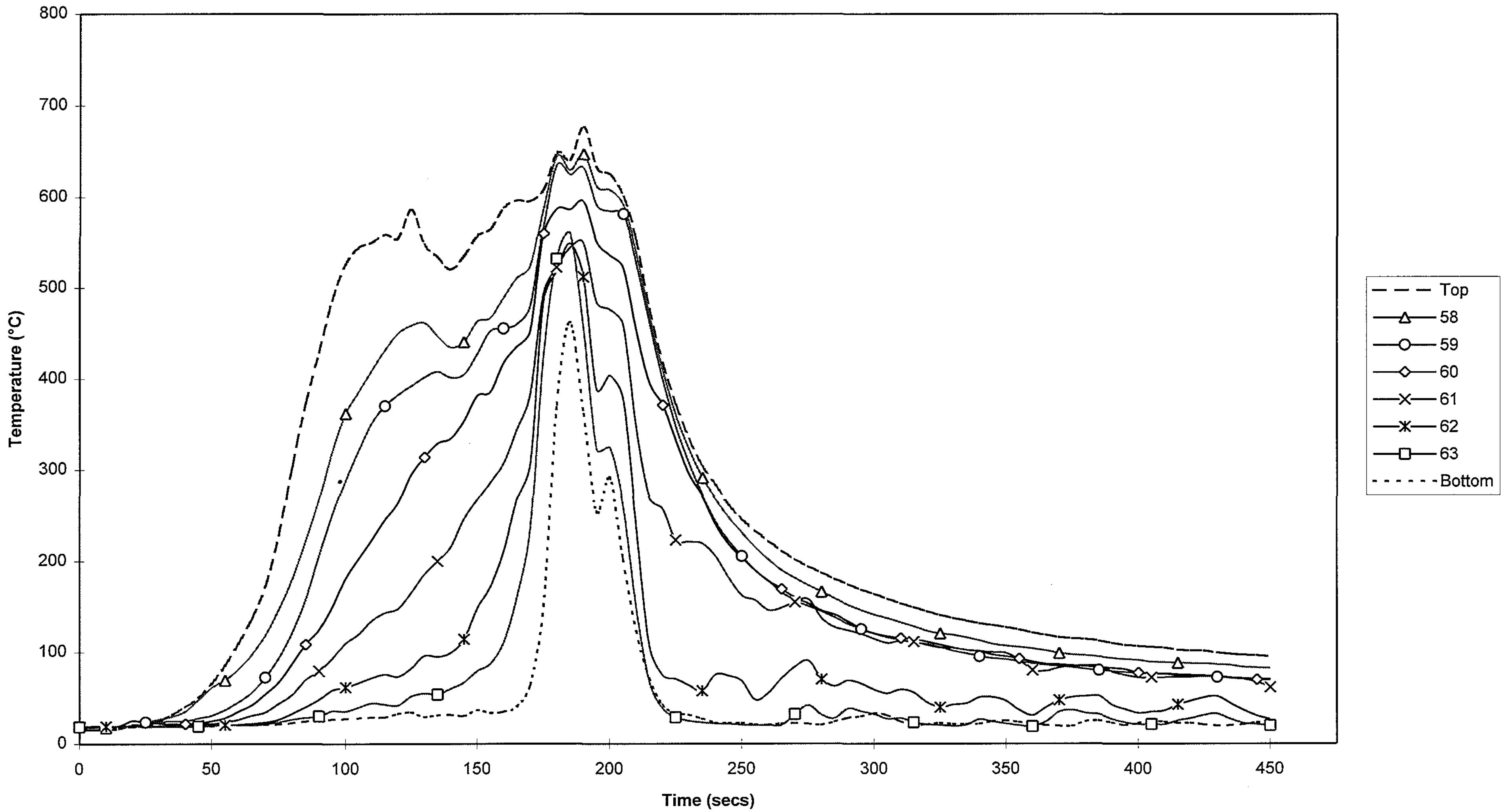
Time vs Temperature Plot for the Room TCT (Experiment 1)

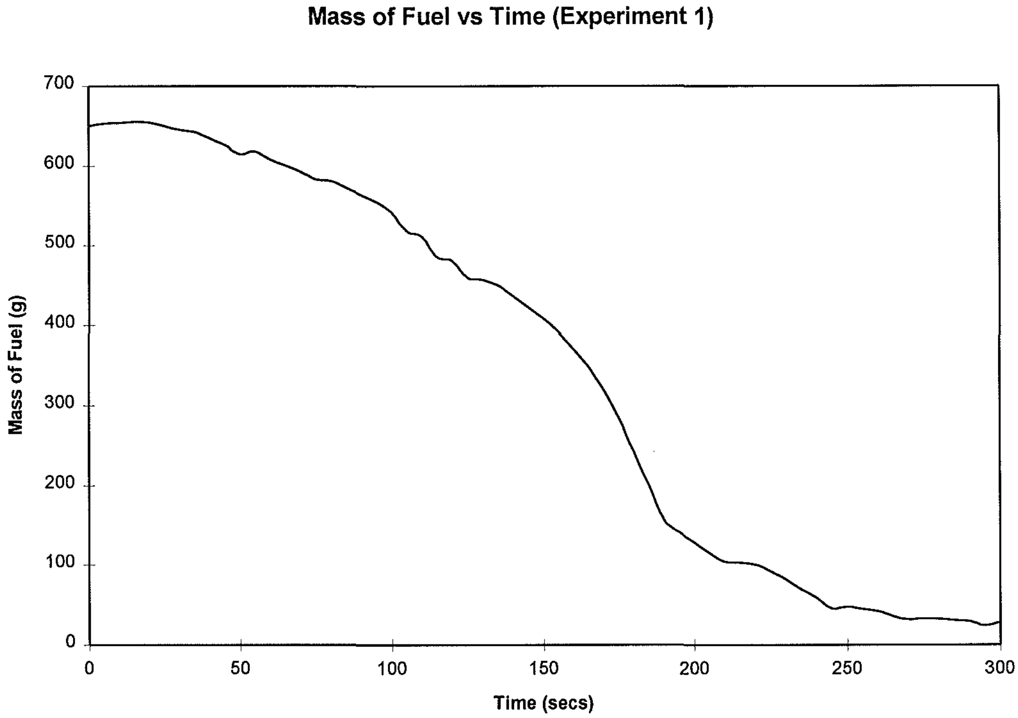


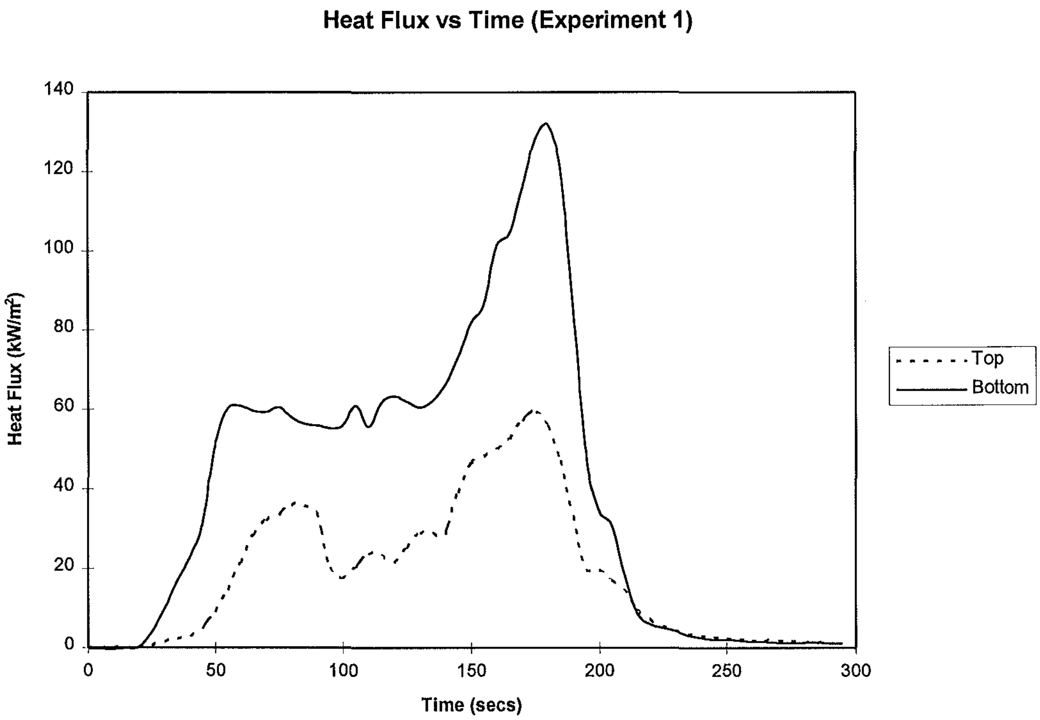


Time vs Temperature Plot for the Corner TCT (Experiment 1)
800
700
600
500
400
300
200
100
0
Temperature (°C)
0
50
100
150
200
250
300
350
400
450
Temperature (°C)
Top
2
3
4
5
6
7
Bottom

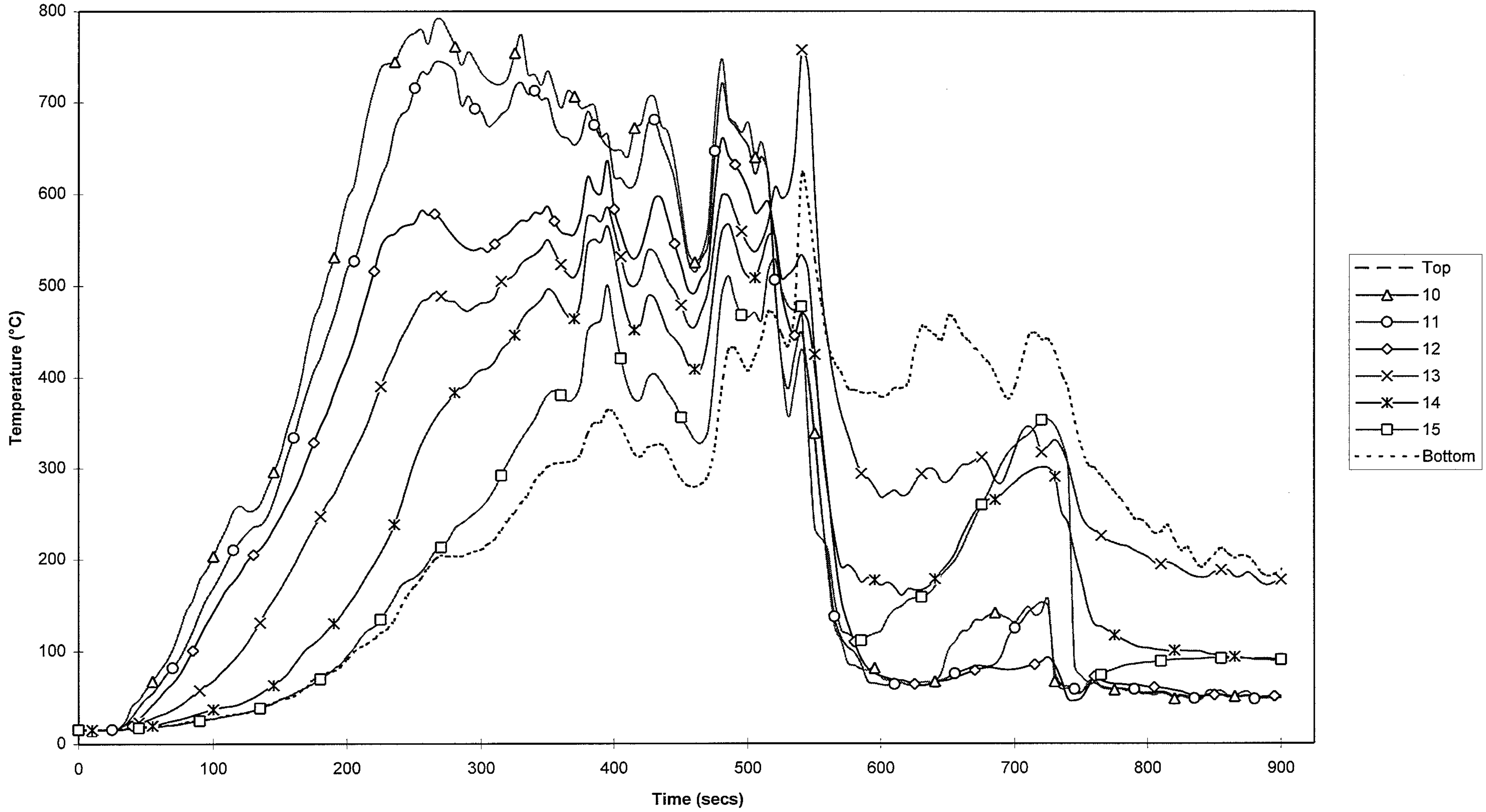
Time vs Temperature Plot for the Vent TCT (Experiment 1)



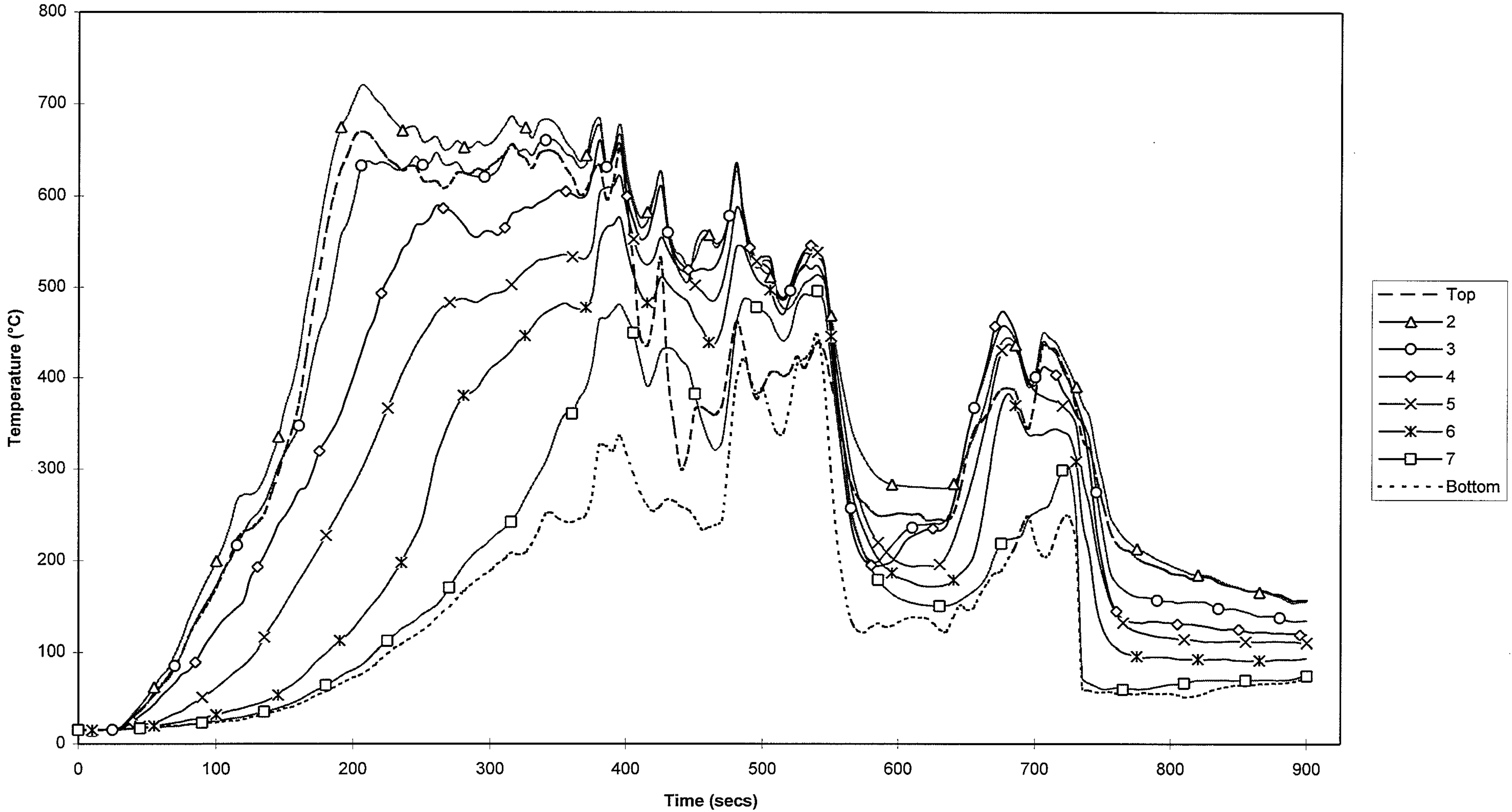

Mass of Fuel vs Time (Experiment 1)
Mass of Fuel (g)
Time (secs)
0
100
200
300
400
500
600
700
0
50
100
150
200
250
300


Heat Flux vs Time (Experiment 1)
Heat Flux (kW/m²)
Time (secs)
0
20
40
60
80
100
120
140
0
50
100
150
200
250
300
Top
Bottom

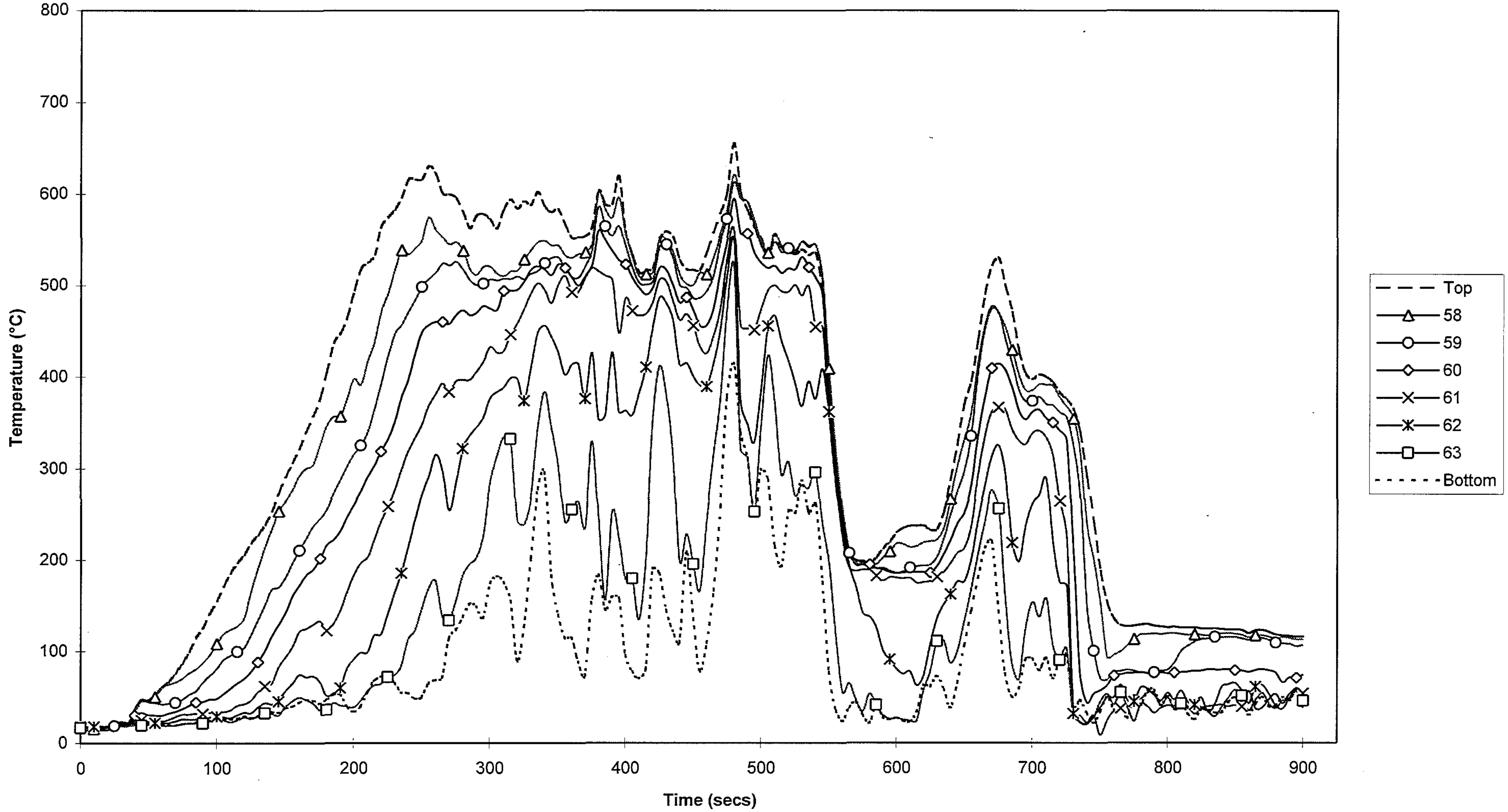
Temperature vs Time Plot for the Room TCT (Experiment 2)

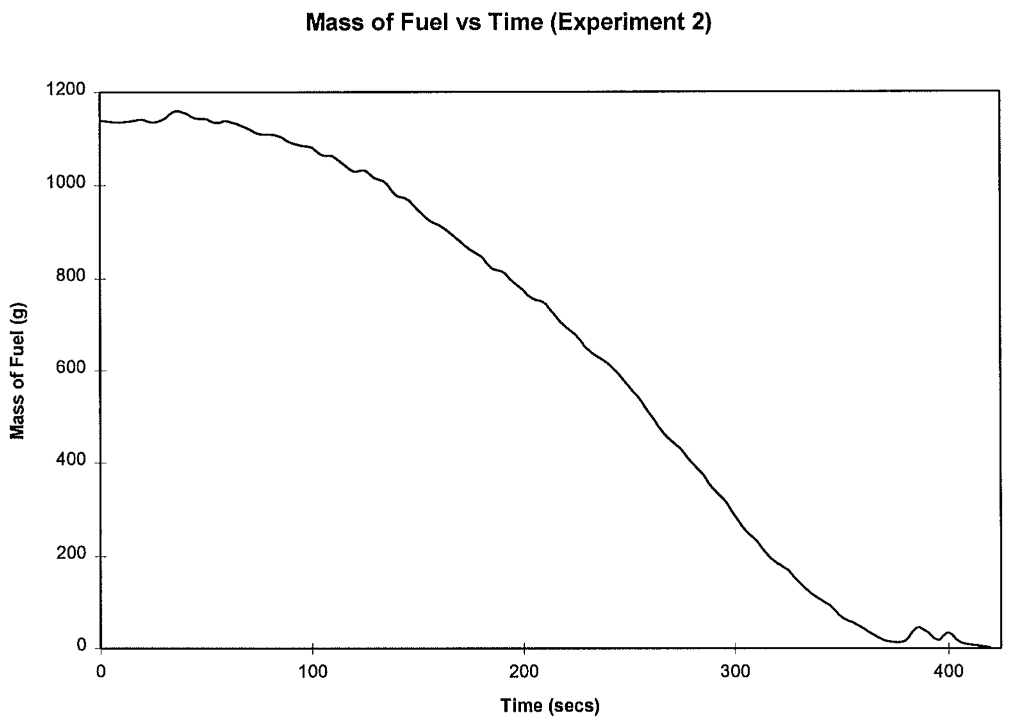


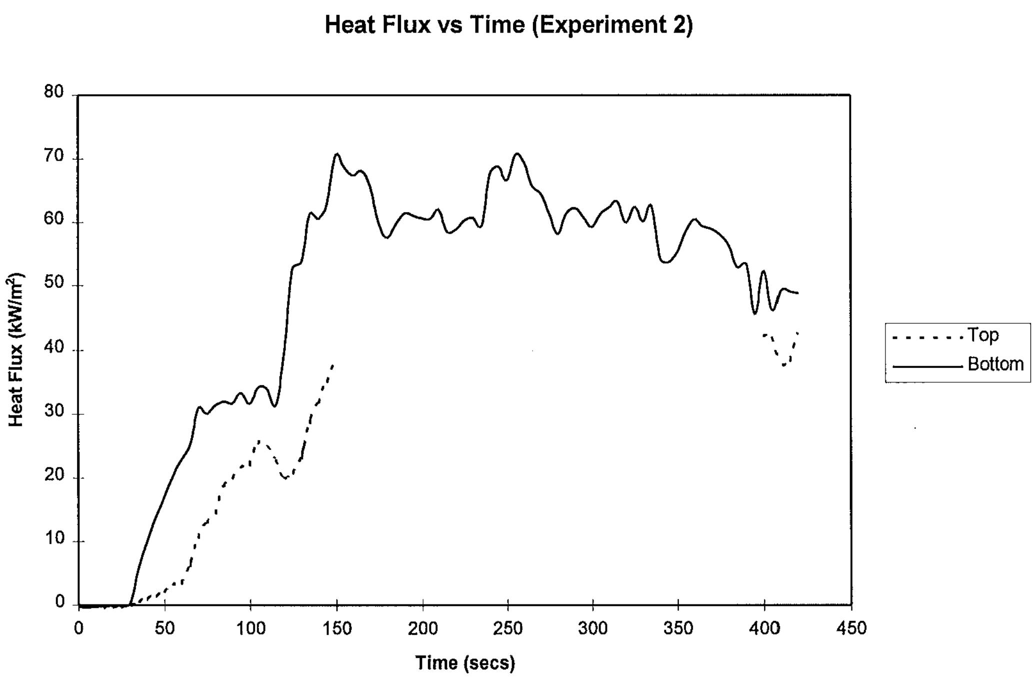
Temperature vs Time Plot for the Corner TCT (Experiment 2)



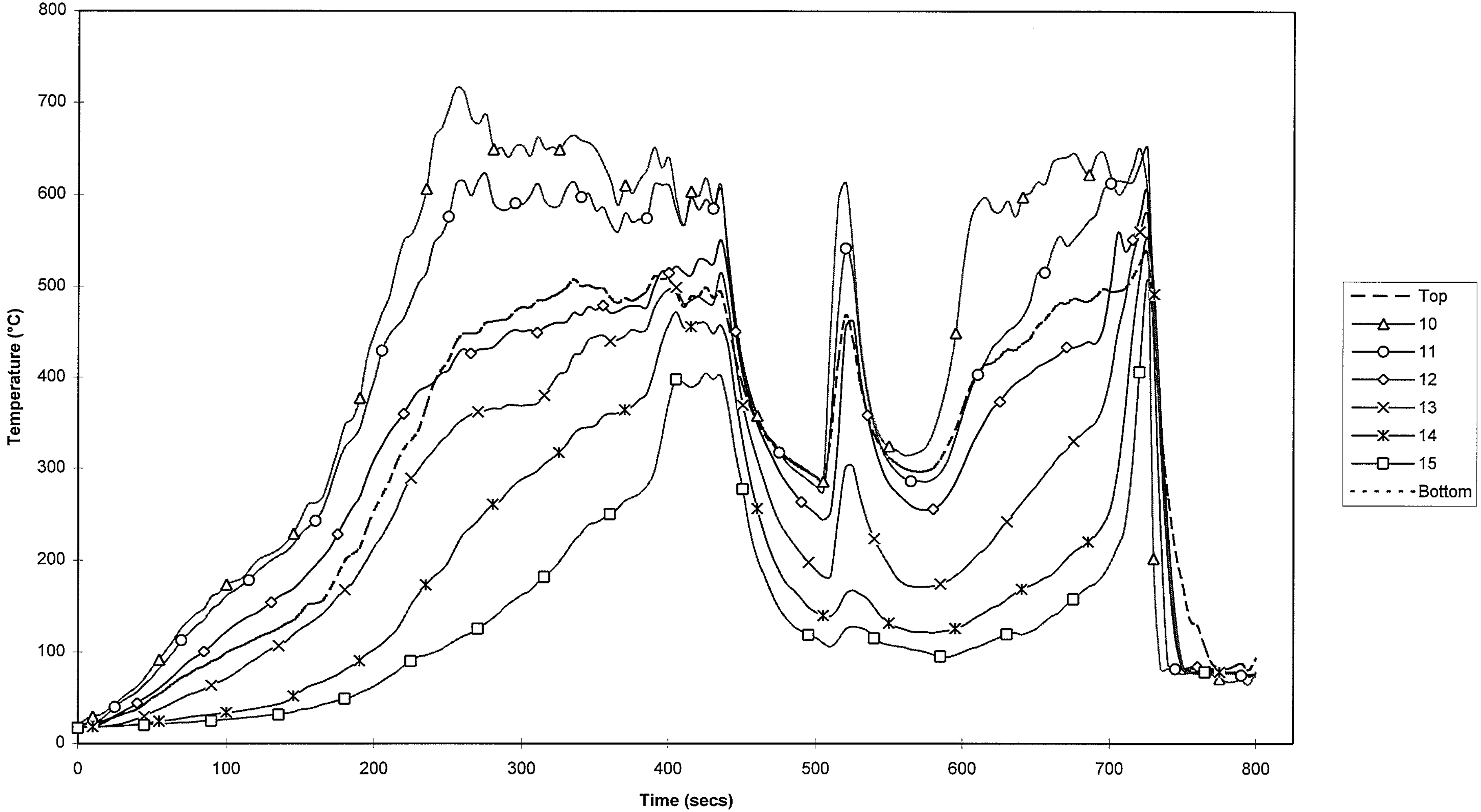
Temperature vs Time Plot for the Vent TCT (Experiment 2)



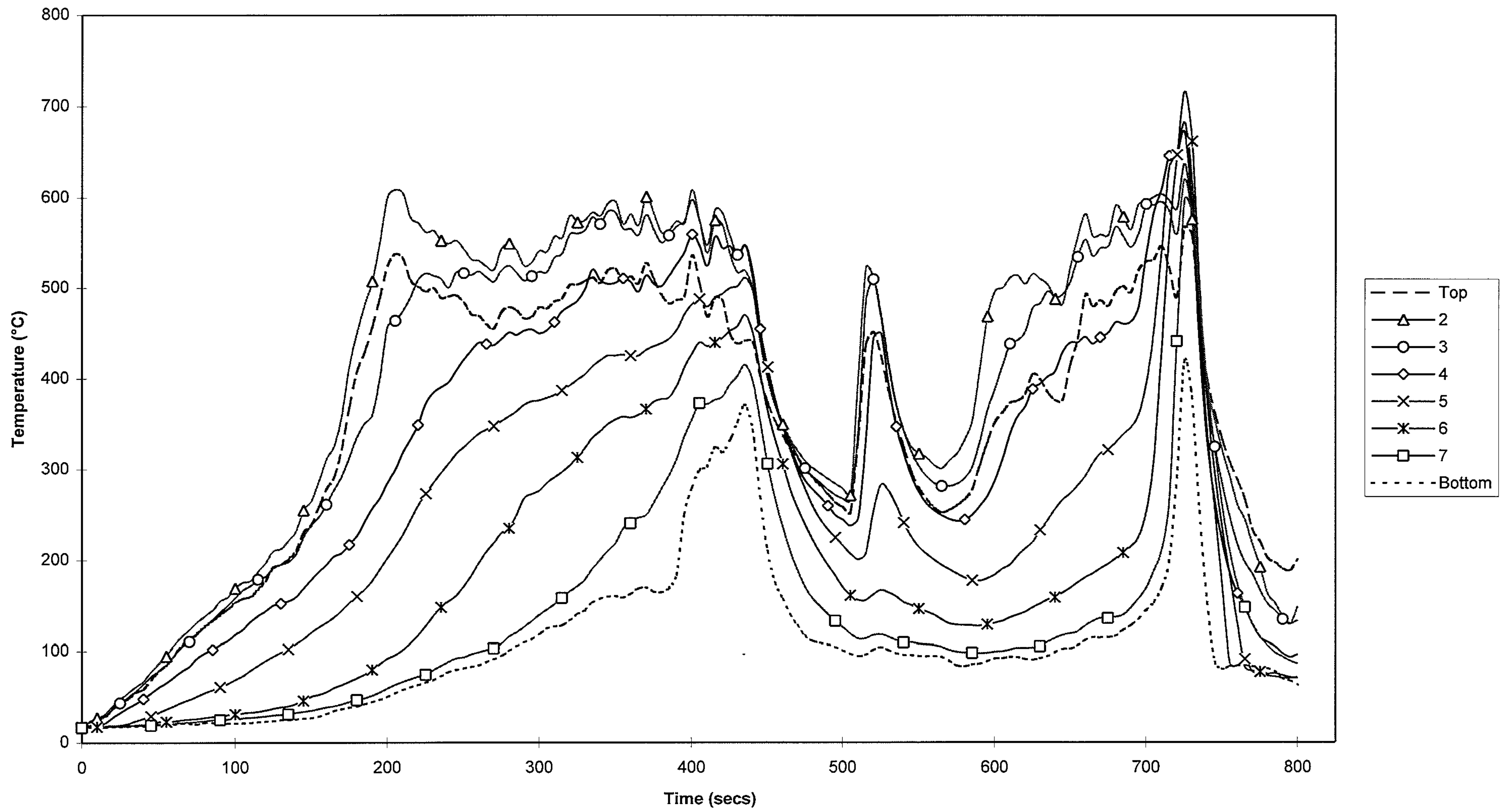

Mass of Fuel vs Time (Experiment 2)
Mass of Fuel (g)
1200
1000
800
600
400
200
0
0
100
200
300
400
Time (secs)

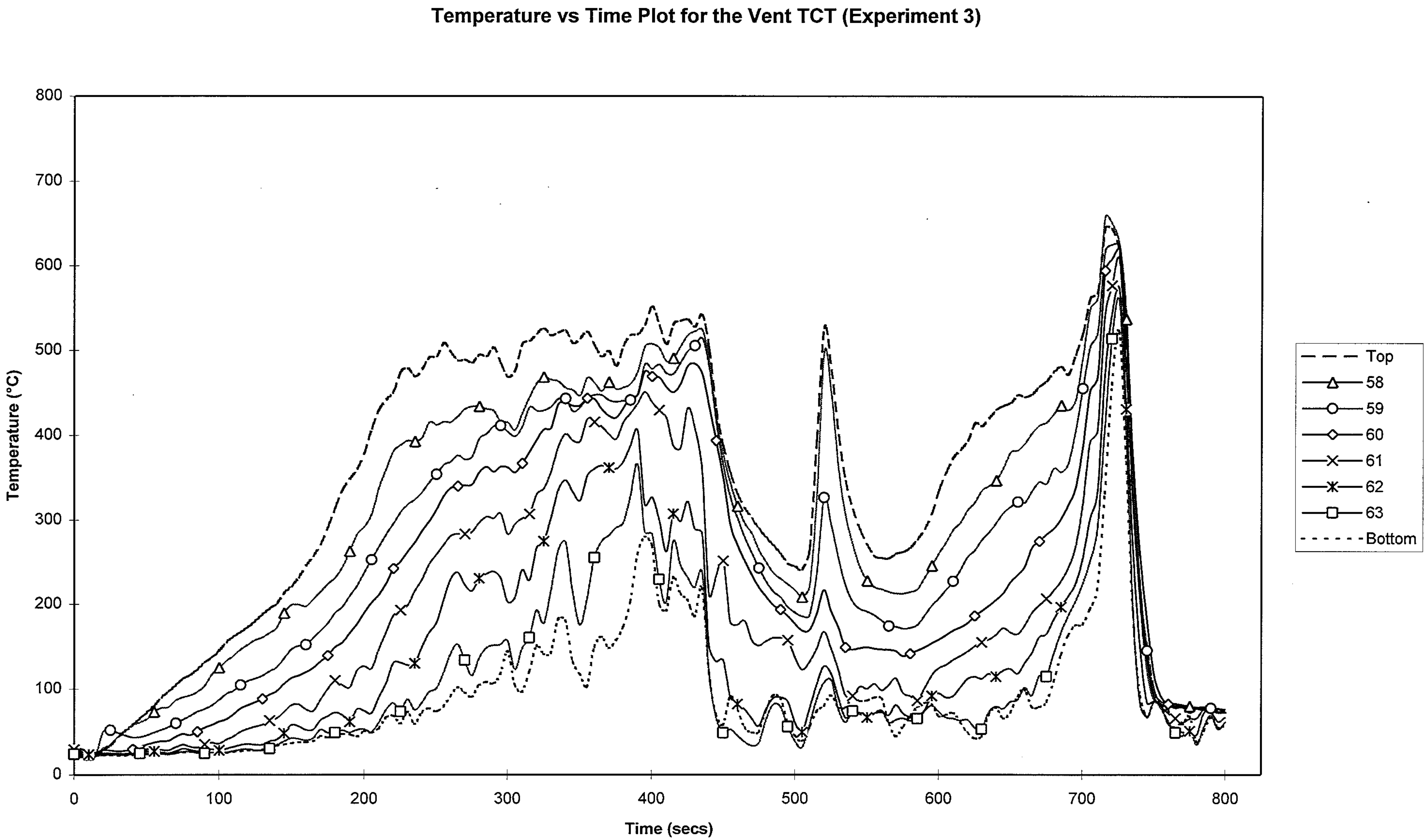

Heat Flux vs Time (Experiment 2)
Heat Flux (kW/m²)
80
70
60
50
40
30
20
10
0
0
50
100
150
200
250
300
350
400
450
Time (secs)
Top
Bottom

Temperature vs Time Plot for the Room TCT (Experiment 3)

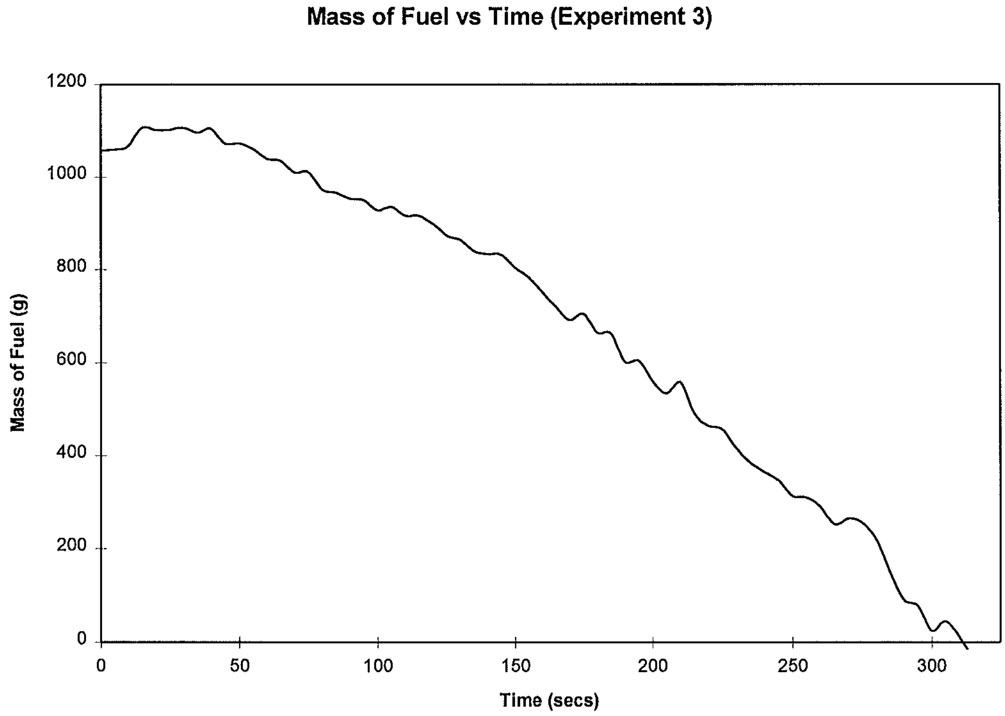


Temperature vs Time Plot for the Corner TCT (Experiment 3)

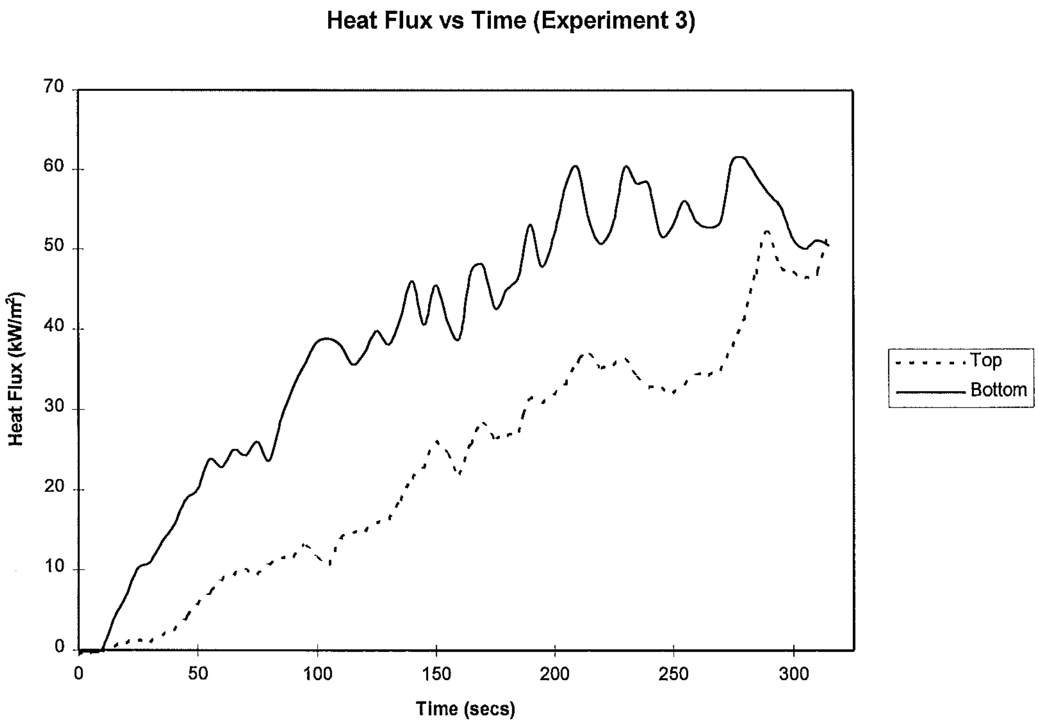




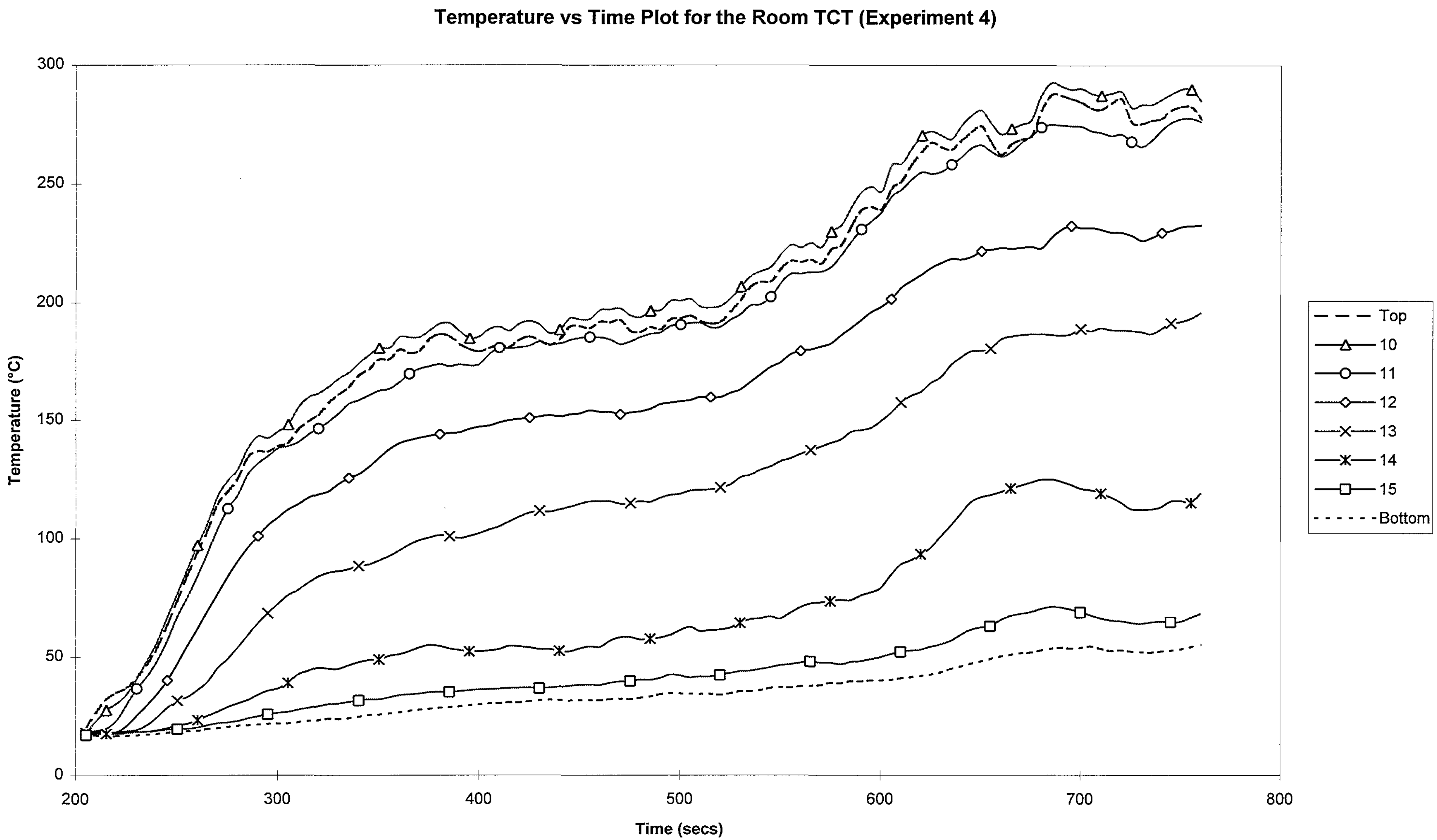
Temperature vs Time Plot for the Vent TCT (Experiment 3)
Temperature (°C)
Time (secs)
0
100
200
300
400
500
600
700
800
Top
58
59
60
61
62
63
Bottom

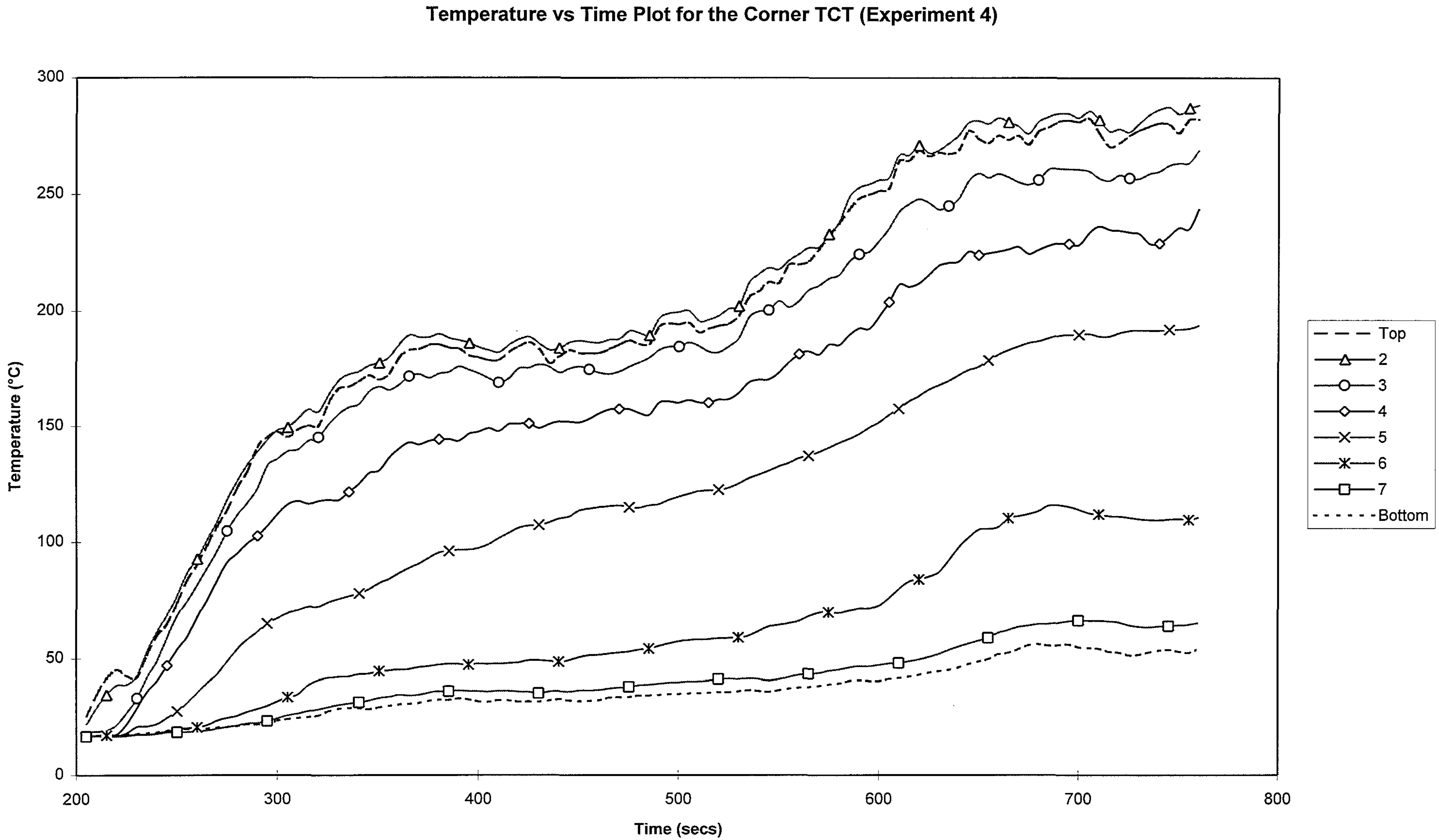


Mass of Fuel vs Time (Experiment 3)
Mass of Fuel (g)
1200
1000
800
600
400
200
0
0
50
100
150
200
250
300
Time (secs)



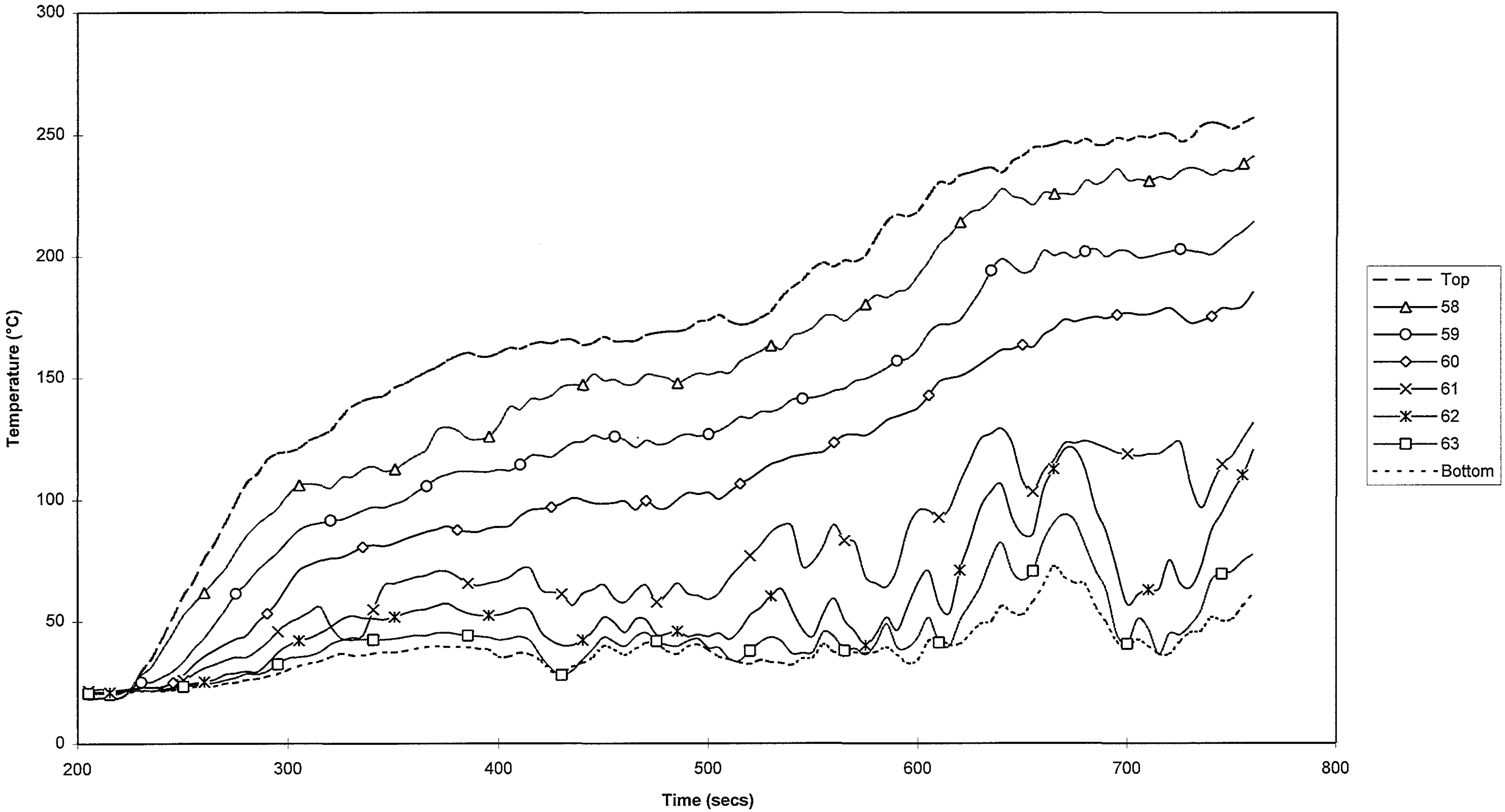
Heat Flux vs Time (Experiment 3)
Heat Flux (kW/m²)
70
60
50
40
30
20
10
0
0
50
100
150
200
250
300
Time (secs)
Top
Bottom

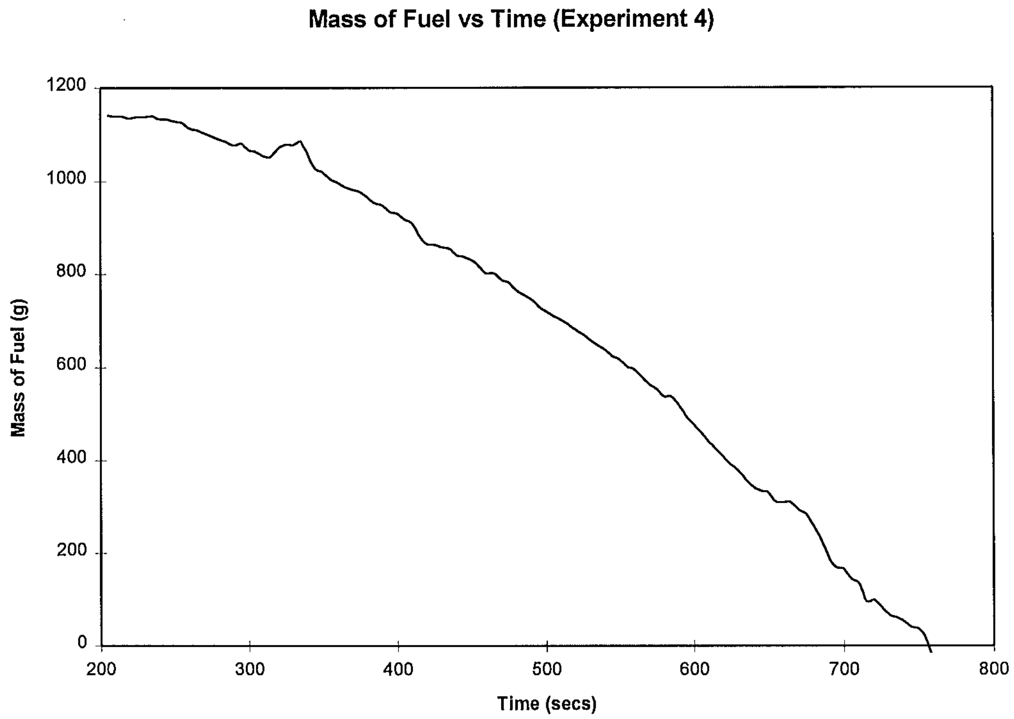

Temperature vs Time Plot for the Room TCT (Experiment 4)
Temperature (°C)
Time (secs)
0
50
100
150
200
250
300
200
300
400
500
600
700
800
Top
10
11
12
13
14
15
Bottom

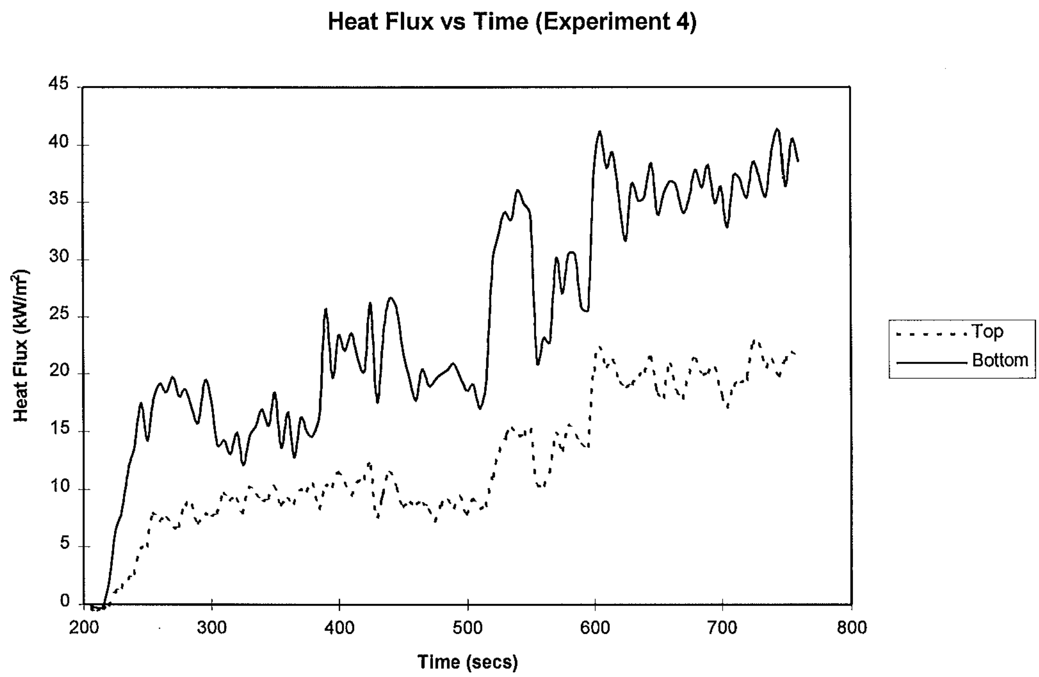


Temperature vs Time Plot for the Corner TCT (Experiment 4)
300
250
200
150
100
50
0
200
300
400
500
600
700
800
Temperature (°C)
Time (secs)
Top
2
3
4
5
6
7
Bottom

Temperature vs Time Plot for the Vent TCT (Experiment 4)




Mass of Fuel vs Time (Experiment 4)
Mass of Fuel (g)
1200
1000
800
600
400
200
0
200
300
400
500
600
700
800
Time (secs)


Heat Flux vs Time (Experiment 4)
Heat Flux (kW/m²)
45
40
35
30
25
20
15
10
5
0
200
300
400
500
600
700
800
Time (secs)
Top
Bottom

A2. APPENDIX 2: SAMPLE CALCULATION

Computation of the interface height, upper layer temperature and lower layer temperature using Coopers N% rule, where N = 10.

Raw Data

Temperature	Height
$T_8 = 179.12$	$H_8 = 2.39$
$T_7 = 185.59$	$H_7 = 2.32$
$T_6 = 173.76$	$H_6 = 2.17$
$T_5 = 147.11$	$H_5 = 1.87$
$T_4 = 102.08$	$H_4 = 1.47$
$T_3 = 52.36$	$H_3 = 1.07$
$T_2 = 36.19$	$H_2 = 0.66$
$T_B = 29.81$	$H_B = 0.26$

Data taken from Experiment 4 at 400 seconds

Compute T_{INT}

$$T_{INT} = C_N \left(T_{MAX} - T_{BOTTOM}\right) + T_{BOTTOM}$$

$$T_{INT} = 0.1 \times (185.59 - 29.81) + 29.81$$

$$T_{INT} = 45.40^{o}\,C$$

Interpolate for Interface Height H_{INT} i.e. height at which 45.40°C is found

$$H_{INT} = \left(\frac{T_{INT} - T_2}{T_3 - T_2} \right) (H_3 - H_2) + H_2$$

$$H_{INT} = \left(\frac{45.40 - 36.19}{52.36 - 36.19} \right) (1.07 - 0.66) + 0.66$$

$$H_{INT} = 0.89\,m$$

Find the Upper Layer Temperature T_{UL}

$$T_{UL} = \int_{H_{INT}}^{H_T} \frac{T(H)}{H_T - H_{INT}} dH$$

Evaluating the above Integral numerically gives

$$T_{UL} = 118.36°C$$

Similarly the Lower Layer Temperature T_{LL} may be evaluated by the following integral

$$T_{UL} = \int_{H_B}^{H_N} \frac{T(H)}{H_{INT} - H_B} dH$$

Evaluating for the above data gives

$$T_{LL} = 35.87°C$$

A3. APPENDIX 3: THERMAL PROPERTY SENSITIVITY ANALYSIS

The following is a sensitivity analysis of the parameters T_{ig} and $k\rho c$ as calculated using Janssens method.

The nominal values for the time to ignition as observed by the cone calorimeter operator are given below.

Nominal Values

Irradiance kW/m^2	**Time to Ignition** secs	**Peak HRR** kW
75	5	195
50	8	145
35	24	422
30	39	114.5
25	52	108

As it can be expected that the operator cannot pin-point the exact time to ignition it is possible to assign a constant percentage error. The results of which may be seen in the table below.

Nominal Time		**+ 5%**	**+ 10%**	**- 5%**	**-10 %**
5 secs	5	5.25	5.5	4.75	4.5
8 secs	8	8.4	8.8	7.6	7.2
24 secs	24	25.2	26.4	22.8	21.6
39 secs	39	40.95	42.9	37.05	35.1
52 secs	52	54.6	57.2	51.3	46.8
$k\rho c$ $(kW/m^2K)^2s$	**0.442**	**0.464**	**0.486**	**0.399**	**0.398**
T_{ig} (°C)	**218.5**	**218.5**	**218.5**	**223.7**	**218.5**

This shows that the value of T_{ig} is relatively insensitive to the percentage error. The above graph is probably not reasonable in reality however where the raw error is more likely to be the same and thus the percentage error will drop with increasing time to ignition. Furthermore the error is most likely to be a recording of the time after ignition has occurred, this error would represent the time taken to react to visually observing that ignition had take place. Thus below we can see the effect of a 1 second over prediction on only the 75 kW/m^2 reading and a corresponding over prediction at all irradiances as maybe more expected.

Nominal Time	**+ 5%**	**+ 10%**	**- 5%**	**-10 %**	**-1 sec**	**-1 sec (all)**
5 secs	5.25	5.5	4.75	4.5	4	4
8 secs	8	8	8	8	8	7
24 secs	24	24	24	24	24	23
39 secs	39	39	39	39	39	38
52 secs	52	52	52	52	52	51
$k\rho c$ (kW/m^{2}K)^{2}s	**0.58**	**0.799**	**0.348**	**0.281**	**0.192**	**0.202**
T_{ig} (°C)	**195.7**	**170.9**	**239.6**	**259.2**	**295**	**284.2**

The outcome of this brief sensitivity analysis is that the value of $k\rho c$ is profoundly affected by the value of the time to ignition data. T_{ig} is affected but not to the same degree. Also found was that by far the most important time to get correct was the time to ignition at the highest irradiance (in this case at 75 kW/m^2). This is also the most variable in terms of percentage error as it is the shortest time and the raw error is likely to stay the same. Therefore the most likely value of the parameters would correspond to a set of times to ignition of 1 second less than that recorded, this gives a net difference over the nominal values of over 50% in terms of $k\rho c$ and around 33% in the case of the T_{ig} term

A4. APPENDIX 4: BRANZFIRE MODEL INPUT AND OUTPUT

The following is the input and output of the simulations run in BRANZFIRE. The first model EXP1A.mod is a complete set of relevant output however the models proceding this do not have the Description of Room and Vent, Thermal Properties of Wall or Floor, Toxicity Parameters, Sprinkler / Detector Parameters, Burning Object Data (for fuel), and some other parameters in the Description of the Fire as these are constant throughout all simulations.

Thursday,January 16,1997,03:43 PM
File EXP1A.mod
BRANZFIRE Room Fire Model (Ver 1.0 Beta - October 1996)
Written by Colleen Wade, BRANZ.

Michelangelo, Observed, Quintiere's, McCaffrey's

==

Description of Room and Vent

==

Room Length (m) =	3.16
Room Width (m) =	2.73
Maximum Room Height (m) =	2.37
Minimum Room Height (m) =	2.37
The room has a flat ceiling.	

Vent No 1

Vent Width (m) =	0.405
Vent Height (m) =	1.000
Vent Sill Height (m) =	0.830
Vent Soffit Height (m) =	1.830
Opening Time (sec) =	0.0

==

Thermal Properties

==

Wall Density (kg/m3) =	790.0
Wall Specific Heat (J/kg.K) =	900.0
Wall Conductivity (W/m.K) =	0.160
Wall Emissivity =	0.90
Wall Thickness (mm) =	25.000

Ceiling Density (kg/m3) =	300.0
Ceiling Specific Heat (J/kg.K) =	1300.0
Ceiling Conductivity (W/m.K) =	0.060

Ceiling Emissivity =	0.90
Ceiling Thickness (mm) =	13.000
Floor Density (kg/m3) =	590.0
Floor Specific Heat (J/kg.K) =	1300.0
Floor Conductivity (W/m.K) =	0.078
Floor Emissivity =	0.50
Floor Thickness = (mm)	25.000

==

Ambient Conditions

==

Interior Temp (C) =	14.0
Exterior Temp (C) =	18.0
Relative Humidity (%) =	65

==

Toxicity Parameters

==

Monitoring Height for FED (m) =	1.50
Occupant Activity Level =	Light

==

Sprinkler / Detector Parameters

==

Response Time Index (m.s)^1/2 =	165.0
Sprinkler C-Factor (m.s)^1/2 =	0.0
Radial Distance (m) =	2.2
Actuation Temperature (C) =	141.0

==

Description of the Fire

==

Radiant Loss Fraction =	0.35
Smoke Emission Coefficent (1/m) =	0.80
Characteristic Mass Loss per Unit Area (kg/s.m2) =	0.003

Air Entrainment in Plume uses McCaffrey's Correlation

Burning Object No 1

Energy Yield (kJ/g) =	42.9
CO Yield (kg/kg fuel) =	0.009
CO2 Yield (kg/kg fuel) =	3.070
Soot Yield (kg/kg fuel) =	0.035
H2O Yield (kg/kg fuel) =	1.465
Fire Height (m) =	0.130
Fire Location (m) =	Corner

This is a simulation of a room-corner test.
Quintiere's Room Corner Model is used.

Flame Length Power =	0.667
Effective heat of combustion (kJ/kg) =	14.0
Heat of gasification (kJ/kg) =	8.0
Maximum energy available (kJ/m2) =	52245.0
Ignition Temperature of Lining (C) =	218.5
Thermal Inertia of Lining =	0.442
Cone HRR Data File Used =	michangl.txt
Flame Area Constant =	0.067
Peak Heat Release Rate (kW/sqm) =	119.2
Burner Width (m) =	0.250

Results from Fire Simulation

Time(min)	HRR(kW)	Layer(m)	U Temp(C)	L Temp(C)
0.00	0.1	2.37	14.0	14.0
0.25	114.7	1.52	90.3	14.5
0.50	168.8	1.07	156.6	16.6
0.75	512.8	0.70	308.7	23.5
1.00	361.1	0.66	520.9	161.0
1.25	562.4	0.91	484.0	138.0
1.50	728.8	0.78	528.9	134.0
1.75	617.7	0.76	524.9	135.4
2.00	566.4	0.83	520.6	137.4
2.25	688.7	0.77	547.9	143.4
2.50	773.3	0.58	572.7	155.8
2.75	758.5	0.35	583.7	176.0
3.00	575.1	0.40	560.1	175.2
3.25	401.1	0.66	528.1	166.8
3.50	492.6	0.88	535.3	159.2
3.75	633.0	0.90	570.3	163.0
4.00	448.1	1.08	549.1	168.1
4.25	515.4	1.16	564.4	172.6
4.50	471.8	1.22	565.4	177.7
4.75	189.2	1.36	528.2	180.2
5.00	232.9	1.51	488.5	184.4
5.25	237.3	1.52	484.8	188.9
5.50	237.8	1.52	482.9	192.4
5.75	238.2	1.52	479.5	195.1
6.00	237.9	1.52	478.4	196.9
6.25	237.7	1.52	478.0	198.2
6.50	237.7	1.52	477.9	199.3
6.75	237.6	1.52	478.0	200.1
7.00	237.6	1.52	478.3	200.9
7.25	237.5	1.52	478.7	201.6
7.50	237.5	1.52	479.2	202.3

Thursday,January 16,1997,04:43 PM
File EXP1B.mod
BRANZFIRE Room Fire Model (Ver 1.0 Beta - October 1996)
Written by Colleen Wade, BRANZ.

Michelangelo, 30 kW/m2, Quintiere's, McCaffrey's

==

Thermal Properties

==

Ceiling Density (kg/m3) =	300.0
Ceiling Specific Heat (J/kg.K) =	1300.0
Ceiling Conductivity (W/m.K) =	0.060
Ceiling Emissivity =	0.90
Ceiling Thickness (mm) =	13.000

==

Ambient Conditions

==

Interior Temp (C) =	14.0
Exterior Temp (C) =	18.0
Relative Humidity (%) =	65

==

Description of the Fire

==

This is a simulation of a room-corner test.
Quintiere's Room Corner Model is used.

Flame Length Power =	0.667
Effective heat of combustion (kJ/kg) =	14.0
Heat of gasification (kJ/kg) =	8.0
Maximum energy available (kJ/m2) =	52245.0
Ignition Temperature of Lining (C) =	284.2
Thermal Inertia of Lining =	0.202
Cone HRR Data File Used =	mich10.txt
Flame Area Constant =	0.067
Peak Heat Release Rate (kW/sqm) =	119.2
Burner Width (m) =	0.250

==

Results from Fire Simulation

==

Time(min)	HRR(kW)	Layer(m)	U Temp(C)	L Temp(C)
0.00	0.1	2.37	14.0	14.0
0.25	114.0	1.52	87.6	14.5
0.50	173.0	1.06	158.0	16.6
0.75	409.0	0.74	292.0	23.1
1.00	2260.0	0.21	675.0	106.0

Time(min)	HRR(kW)	Layer(m)	U Temp(C)	L Temp(C)
1.25	555.0	0.90	481.0	123.0
1.50	140.0	1.04	297.0	106.0
1.75	113.0	0.90	263.0	85.6
2.00	84.6	0.91	239.0	71.0
2.25	131.0	0.83	234.0	61.2
2.50	206.0	0.60	259.0	54.5
2.75	337.0	0.29	315.0	54.2
3.00	205.0	0.36	326.0	60.0
3.25	73.4	0.64	278.0	57.4
3.50	61.8	0.90	234.0	52.7
3.75	87.9	0.94	216.0	48.9
4.00	27.5	1.04	197.0	45.7
4.25	25.3	1.15	169.0	43.1
4.50	11.5	1.21	146.0	40.8
4.75	0.1	1.28	126.0	39.0
5.00	0.1	1.41	114.0	37.8
5.25	0.1	1.47	103.0	37.1
5.50	0.1	1.49	94.3	36.6
5.75	0.1	1.50	87.1	36.1
6.00	0.1	1.49	81.3	35.6
6.25	0.1	1.49	76.6	35.0
6.50	0.1	1.48	72.7	34.4
6.75	0.1	1.48	69.3	33.9
7.00	0.1	1.47	66.4	33.3
7.25	0.1	1.46	63.9	32.7
7.50	0.1	1.46	61.7	32.1
7.75	0.1	1.45	59.7	31.6
8.00	0.1	1.45	57.8	31.1
8.25	0.1	1.44	56.2	30.6

Thursday,January 16,1997,03:30 PM
File EXP2A.mod
BRANZFIRE Room Fire Model (Ver 1.0 Beta - October 1996)
Written by Colleen Wade, BRANZ.

Flameguard, 30kW/m2, Quintiere, McCaffrey

==

Thermal Properties

==

Ceiling Density (kg/m3) =	300.0
Ceiling Specific Heat (J/kg.K) =	1300.0
Ceiling Conductivity (W/m.K) =	0.060
Ceiling Emissivity =	0.90
Ceiling Thickness (mm) =	12.500

==

Ambient Conditions

==

Interior Temp (C) =	15.0
Exterior Temp (C) =	17.0
Relative Humidity (%) =	65

==

Description of the Fire

==

This is a simulation of a room-corner test.
Quintiere's Room Corner Model is used.

Flame Length Power =	0.667
Effective heat of combustion (kJ/kg) =	14.0
Heat of gasification (kJ/kg) =	12.6
Maximum energy available (kJ/m2) =	45362.0
Ignition Temperature of Lining (C) =	131.4
Thermal Inertia of Lining =	2.809
Cone HRR Data File Used =	flamg1.txt
Flame Area Constant =	0.067
Peak Heat Release Rate (kW/sqm) =	134.0
Burner Width (m) =	0.250

==

Results from Fire Simulation

==

Time(min)	HRR(kW)	Layer(m)	U Temp(C)	L Temp(C)
0.00	0.1	2.37	15.0	15.0
0.25	164.0	1.40	111.8	15.6
0.50	80.0	1.01	151.1	17.9
0.75	97.7	0.96	160.1	20.2
1.00	153.4	0.83	189.6	22.9

Time(min)	HRR(kW)	Layer(m)	U Temp(C)	L Temp(C)
1.25	141.4	0.78	217.6	26.5
1.50	232.2	0.67	241.8	29.9
1.75	242.7	0.55	279.0	35.9
2.00	247.2	0.54	297.3	42.1
2.25	261.8	0.55	310.3	47.2
2.50	263.4	0.56	320.3	51.4
2.75	301.9	0.53	334.7	55.3
3.00	321.0	0.48	351.3	60.3
3.25	330.8	0.47	363.0	65.8
3.50	414.1	0.37	388.4	72.6
3.75	373.9	0.39	401.1	77.2
4.00	412.9	0.38	411.7	80.0
4.25	426.1	0.37	425.3	83.0
4.50	380.1	0.42	425.4	87.2
4.75	365.0	0.49	422.8	88.4
5.00	348.6	0.56	421.4	88.4
5.25	313.3	0.68	417.3	87.6
5.50	211.3	0.98	401.6	85.9
5.75	195.8	1.28	393.4	85.2
6.00	194.3	1.46	406.3	89.5
6.25	192.1	1.51	409.6	96.1
6.50	190.2	1.52	411.2	102.8
6.75	188.7	1.52	412.4	109.1
7.00	187.8	1.52	413.7	114.8
7.25	187.4	1.52	415.2	120.1
7.50	187.4	1.52	417.0	124.9
7.75	187.9	1.52	419.0	129.4
8.00	188.8	1.52	421.3	133.5
8.25	190.1	1.52	423.9	137.4
8.50	191.7	1.52	426.7	141.0
8.75	193.7	1.52	429.8	144.6
9.00	195.9	1.52	433.2	148.0
9.25	198.5	1.52	436.7	151.5
9.50	201.4	1.52	440.5	154.8
9.75	204.5	1.52	444.5	158.3
10.00	207.9	1.52	448.7	161.7

Wednesday,January 15,1997,11:18 AM
File EXP2B.mod
BRANZFIRE Room Fire Model (Ver 1.0 Beta - October 1996)
Written by Colleen Wade, BRANZ.

Flameguard, observed, Quintiere, McCaffrey

==

Thermal Properties

==

Ceiling Density (kg/m3) =	300.0
Ceiling Specific Heat (J/kg.K) =	1300.0
Ceiling Conductivity (W/m.K) =	0.060
Ceiling Emissivity =	0.90
Ceiling Thickness (mm) =	12.500

==

Ambient Conditions

==

Interior Temp (C) =	15.0
Exterior Temp (C) =	17.0
Relative Humidity (%) =	65

==

Description of the Fire

==

This is a simulation of a room-corner test.
Quintiere's Room Corner Model is used.

Flame Length Power =	0.667
Effective heat of combustion (kJ/kg) =	14.0
Heat of gasification (kJ/kg) =	12.6
Maximum energy available (kJ/m2) =	45362.0
Ignition Temperature of Lining (C) =	131.4
Thermal Inertia of Lining =	1.942
Cone HRR Data File Used =	flamgard.txt
Flame Area Constant =	0.067
Peak Heat Release Rate (kW/sqm) =	134.0
Burner Width (m) =	0.250

==

Results from Fire Simulation

==

Time(min)	HRR(kW)	Layer(m)	U Temp(C)	L Temp(C)
0.00	0.1	2.37	15.0	15.0
0.25	165.3	1.40	112.4	15.6
0.50	82.4	1.01	152.7	17.9
0.75	119.2	0.94	167.1	20.4
1.00	159.2	0.82	202.0	23.5

Time(min)	HRR(kW)	Layer(m)	U Temp(C)	L Temp(C)
1.25	158.3	0.80	220.0	27.2
1.50	237.6	0.67	256.6	31.3
1.75	248.2	0.57	286.6	37.4
2.00	253.9	0.56	303.0	43.5
2.25	269.9	0.56	316.1	48.5
2.50	273.2	0.57	326.9	52.8
2.75	313.6	0.53	342.3	57.0
3.00	335.1	0.48	359.4	62.6
3.25	347.2	0.47	372.2	68.5
3.50	433.4	0.37	399.0	76.0
3.75	396.1	0.39	412.7	79.0
4.00	438.1	0.38	424.5	83.9
4.25	454.8	0.36	440.1	88.2
4.50	412.0	0.42	442.6	93.6
4.75	399.9	0.49	442.1	95.9
5.00	386.8	0.56	443.2	96.8
5.25	339.4	0.68	438.6	96.6
5.50	235.5	0.98	421.9	94.7
5.75	219.2	1.28	415.5	94.2
6.00	218.0	1.46	429.7	99.5
6.25	216.2	1.51	434.0	107.5
6.50	214.6	1.52	436.4	115.6
6.75	213.8	1.52	438.4	123.2
7.00	213.6	1.52	440.7	130.3
7.25	214.1	1.52	443.3	136.7
7.50	215.3	1.52	446.2	142.7
7.75	217.1	1.52	449.5	148.3

Wednesday,February 19,1997,12:09 AM
EXP3A.mod
BRANZFIRE Room Fire Model (Ver 1.0 Beta - October 1996)
Written by Colleen Wade, BRANZ.

Hardboard, book (quint 2-210), Quintiere, McCaffrey

==

Thermal Properties

==

Ceiling Density (kg/m3) =	960.0
Ceiling Specific Heat (J/kg.K) =	1380.0
Ceiling Conductivity (W/m.K) =	0.150
Ceiling Emissivity =	0.85
Ceiling Thickness (mm) =	6.000

==

Ambient Conditions

==

Interior Temp (C) =	18.0
Exterior Temp (C) =	24.0
Relative Humidity (%) =	65

==

Description of the Fire

==

This is a simulation of a room-corner test.
Quintiere's Room Corner Model is used.

Flame Length Power =	0.667
Effective heat of combustion (kJ/kg) =	15.0
Heat of gasification (kJ/kg) =	6.0
Maximum energy available (kJ/m2) =	62782.9
Ignition Temperature of Lining (C) =	298.0
Thermal Inertia of Lining =	1.870
Cone HRR Data File Used =	hardbook.txt
Flame Area Constant =	0.067
Peak Heat Release Rate (kW/sqm) =	292.0
Burner Width (m) =	0.250

==

Results from Fire Simulation

==

Time(min)	HRR(kW)	Layer(m)	U Temp(C)	L Temp(C)
0.00	0.1	2.35	18.0	18.0
0.25	337.8	1.08	181.9	19.9
0.50	188.9	0.53	241.2	29.0
0.75	186.3	0.53	245.4	36.7

Time(min)	HRR(kW)	Layer(m)	U Temp(C)	L Temp(C)
1.00	147.9	0.62	242.5	40.9
1.25	247.4	0.58	261.6	43.7
1.50	328.1	0.46	309.4	50.0
1.75	572.6	0.33	392.6	65.3
2.00	707.5	0.48	505.9	124.3
2.50	220.5	0.63	378.1	115.9
2.75	176.7	0.61	323.5	93.3
3.00	242.3	0.48	319.1	78.2
3.25	221.6	0.41	322.0	73.0
3.50	166.6	0.48	307.2	69.6
3.75	107.4	0.63	280.2	65.2
4.00	403.7	0.29	331.5	64.9
4.25	0.1	0.59	299.5	69.0
4.50	0.1	1.20	226.6	63.9
4.75	0.1	1.45	184.1	61.7
5.00	0.1	1.52	157.4	60.8
5.25	0.1	1.53	140.7	60.1
5.50	0.1	1.53	129.4	59.1
5.75	0.1	1.52	121.2	58.1
6.00	0.1	1.51	114.8	56.9
6.25	0.1	1.51	109.6	55.6
6.50	0.1	1.50	105.2	54.3
6.75	0.1	1.49	101.2	53.1
7.00	0.1	1.49	97.7	51.9
7.25	0.1	1.49	94.5	50.7
7.50	0.1	1.48	91.6	49.5
7.75	0.1	1.48	88.9	48.4
8.00	0.1	1.48	86.4	47.2
8.25	0.1	1.47	84.0	46.2
8.50	0.1	1.47	81.7	45.2
8.75	0.1	1.47	79.6	44.3
9.00	0.1	1.46	77.6	43.4
9.25	0.1	1.46	75.7	42.6
9.50	0.1	1.46	74.0	41.8
9.75	0.1	1.45	72.3	41.0
10.00	0.1	1.45	70.7	40.3

Thursday,January 16,1997,01:44 PM
File EXP3B.mod
BRANZFIRE Room Fire Model (Ver 1.0 Beta - October 1996)
Written by Colleen Wade, BRANZ.

Hardboard, 30 kW/m2, Quintiere, McCaffrey

==

Thermal Properties

==

Ceiling Density (kg/m3) =	960.0
Ceiling Specific Heat (J/kg.K) =	1380.0
Ceiling Conductivity (W/m.K) =	0.150
Ceiling Emissivity =	0.85
Ceiling Thickness (mm) =	6.000

==

Ambient Conditions

==

Interior Temp (C) =	18.0
Exterior Temp (C) =	24.0
Relative Humidity (%) =	65

==

Description of the Fire

==

This is a simulation of a room-corner test.
Quintiere's Room Corner Model is used.

Flame Length Power =	0.667
Effective heat of combustion (kJ/kg) =	15.0
Heat of gasification (kJ/kg) =	3.2
Maximum energy available (kJ/m2) =	62782.9
Ignition Temperature of Lining (C) =	190.2
Thermal Inertia of Lining =	2.055
Cone HRR Data File Used =	hard2.txt
Flame Area Constant =	0.067
Peak Heat Release Rate (kW/sqm) =	292.0
Burner Width (m) =	0.250

==

Results from Fire Simulation

==

Time(min)	HRR(kW)	Layer(m)	U Temp(C)	L Temp(C)
0.00	0.1	2.35	18.0	18.0
0.25	448.1	1.06	249.5	21.1
0.50	5970.8	0.02	724.1	83.8
0.75	550.1	0.68	502.2	144.1
1.00	397.5	0.73	476.7	132.6

Time(min)	HRR(kW)	Layer(m)	U Temp(C)	L Temp(C)
1.25	561.2	0.64	499.4	128.7
1.50	525.2	0.59	499.1	131.0
1.75	579.4	0.52	508.0	134.8
2.00	624.1	0.43	516.9	141.8
2.25	547.1	0.43	511.3	145.5
2.50	600.7	0.39	521.7	149.1
2.75	533.2	0.42	519.2	152.0
3.00	614.1	0.37	534.1	155.8
3.25	571.1	0.37	534.8	157.6
3.50	513.2	0.42	532.8	161.1
3.75	432.2	0.52	530.1	161.3
4.00	726.8	0.29	573.3	176.1
4.25	29.0	0.59	511.3	171.5
4.50	31.1	1.08	401.0	151.1
4.75	15.7	1.26	317.2	133.2
5.00	4.2	1.31	276.5	119.5
5.25	0.1	1.45	256.6	110.7
5.50	0.1	1.51	237.4	106.9
5.75	0.1	1.53	221.9	104.2
6.00	0.1	1.53	209.8	101.5
6.25	0.1	1.53	199.8	98.6
6.50	0.1	1.53	191.3	95.6
6.75	0.1	1.53	183.7	92.6
7.00	4.4	1.50	174.7	89.6
7.25	84.9	1.25	194.7	82.9
7.50	108.4	1.03	242.3	74.3
7.75	64.4	1.04	241.4	68.2
8.00	17.0	1.19	213.8	64.1
8.25	9.2	1.31	180.6	61.2
8.50	225.2	1.04	238.1	58.8
8.75	120.4	0.97	294.4	59.3
9.00	0.1	1.23	230.0	58.5
9.25	0.1	1.46	189.4	58.0
9.50	14.7	1.50	164.1	58.4
9.75	961.4	0.71	596.6	92.8
10.00	115.0	1.08	439.7	112.9

Wednesday,January 15,1997,12:33 PM
File EXP4A.mod
BRANZFIRE Room Fire Model (Ver 1.0 Beta - October 1996)
Written by Colleen Wade, BRANZ.

Gypsum, Quintiere,

==

Thermal Properties

==

Ceiling Density (kg/m3) =	790.0
Ceiling Specific Heat (J/kg.K) =	900.0
Ceiling Conductivity (W/m.K) =	0.160
Ceiling Emissivity =	0.85
Ceiling Thickness (mm) =	25.000

==

Ambient Conditions

==

Interior Temp (C) =	17.0
Exterior Temp (C) =	21.0
Relative Humidity (%) =	65

==

Description of the Fire

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This is a simulation of a room-corner test.
Quintiere's Room Corner Model is used.

Flame Length Power =	0.667
Effective heat of combustion (kJ/kg) =	7.0
Heat of gasification (kJ/kg) =	4.8
Maximum energy available (kJ/m2) =	2092.8
Ignition Temperature of Lining (C) =	469.0
Thermal Inertia of Lining =	0.515
Cone HRR Data File Used =	3111hrr.txt
Flame Area Constant =	0.067
Peak Heat Release Rate (kW/sqm) =	81.7
Burner Width (m) =	0.250

==

Results from Fire Simulation

==

Time(min)	HRR(kW)	Layer(m)	U Temp(C)	L Temp(C)
0.00	0.1	2.37	17.0	17.0
0.25	109.5	1.50	79.9	17.4
0.50	72.9	1.11	120.8	19.1
0.75	56.5	1.04	130.6	21.1
1.00	65.2	1.01	133.6	22.8

Time(min)	HRR(kW)	Layer(m)	U Temp(C)	L Temp(C)
1.25	28.0	1.06	127.1	24.1
1.50	6.4	1.17	106.2	24.7
1.75	164.3	0.89	136.8	25.6
2.00	81.4	0.71	168.1	27.7
2.25	70.0	0.78	164.7	29.1
2.50	81.3	0.81	163.6	30.1
2.75	100.6	0.77	171.1	31.0
3.00	118.3	0.70	185.0	32.0
3.25	52.4	0.78	179.4	32.8
3.50	80.6	0.86	169.6	33.0
3.75	74.3	0.86	169.0	33.1
4.00	100.4	0.81	174.7	33.3
4.25	101.7	0.75	184.6	33.8
4.50	82.8	0.77	185.6	34.2
4.75	95.2	0.78	185.6	34.6
5.00	93.7	0.77	188.3	34.9
5.25	100.6	0.76	191.7	35.1
5.50	117.0	0.72	199.9	35.6
5.75	100.0	0.72	203.5	36.3
6.00	167.1	0.63	219.4	37.3
6.25	151.5	0.55	235.3	39.5
6.50	140.0	0.56	237.8	41.3
6.75	103.8	0.66	229.5	41.8
7.00	66.3	0.81	209.5	41.2
7.25	139.4	0.78	211.0	40.7
7.50	244.3	0.49	252.8	42.0
7.75	149.3	0.46	266.9	46.2
8.00	125.7	0.59	252.1	46.8
8.25	103.0	0.72	237.5	45.9
8.50	10.5	0.99	204.0	44.3
8.75	10.8	1.33	172.5	42.9
9.00	10.9	1.46	150.9	42.4
9.25	10.8	1.50	136.7	42.2
9.50	10.7	1.51	127.4	41.9
9.75	10.4	1.51	120.8	41.7
10.00	10.2	1.51	116.0	41.2

A5. APPENDIX 5: QUINTIERE'S MODEL INPUT DATA

The following is an explanation of format of text file input into Quintiere's model.

Sample value	Variable Description	[Units] / Defualt Values
3111hrr (material s4)	Run Description	[40 Characters Max], -*
290	Ambient Temperature	[K], 293
3.44	Gas Parameter	[(kW/m$^{5/2}$K], 3.44
0.546	Thermal Inertia	[(kW/m^{2}K)^{2}s], -
1	Vent Height	[m], -
0.405	Vent Width	[m], -
1.3	Igntion Region Height	[m], -
0.17	Ignition Region Half Width	[m], -
2.945	Max Distance in X Direction	[m], -
5.185	Max Distance in Y Direction	[m], -
2.0608	Max Distance in Z Direction	[m], -
100	Ignitor HRR	[kW], -
46.08	Suface Area of Room	[m^2], -
42.8142	Pyrolysis Region Net Heat Flux	[kW/m^2], -
7	Heat of Combustion	[kJ/g], -
4.8	Heat of Gasification	[kJ/g], -
0	Configuration Radiant Incident Heat Flux	[kW/m^2], 0.0
0.01	Tolerance on Iterations	[ ]**, 0.01
0.25	Parameter for Ceiling Area	[ ], 0.0
60	Ignitor Incident Heat Flux	[kW/m^2], 60
85.8538	Ignitor HRR per unit Width	[kW/m], -
0.0667	Flame Length Coefficient	[m^2/kW], 0.01
0.667	Flame Length Power	[ ], -
2092.8	Total Energy per unit Area	[kJ/m^2], -
776	Ignition Temperature	[K], -
14.7	Lateral Flame Spread Parameter	[kW^2/m^3], -
2.37	Height above Burner Surface	[m], -
2.73	Room Width	[m], -
3.16	Room Depth	[m], -
30	Incident Flame Heat Flux in Spread	[kW/m^2], -
30000	Max Fire Size	[kW], -
653	Min Temperature for flame Spread	[K], -
1	Time Step	[s], -

* Denotes user specified, no default
** Denotes dimensionless value

The following are the input text files used in the simulations with Quintiere's model.

EXP1A.csv	**EXP1C.csv**
Fibreboard, Observed	Fibreboard, 30 kW/m2
287	287
3.44	3.44
0.442	0.202
1	1
0.405	0.405
1.3	1.3
0.17	0.17
2.945	2.945
5.185	5.185
2.0608	2.0608
101.8	101.8
45.1722	45.1722
56.6914	54.5349
14	14
4.2	4.2
0	0
0.01	0.01
0.25	0.25
60	60
85.8538	85.8538
0.0667	0.0667
0.667	0.667
52245	52245
491.5	557.2
14	14
2.24	2.24
3.16	3.16
2.73	2.73
30	30
50000	30000
363	363
5	5

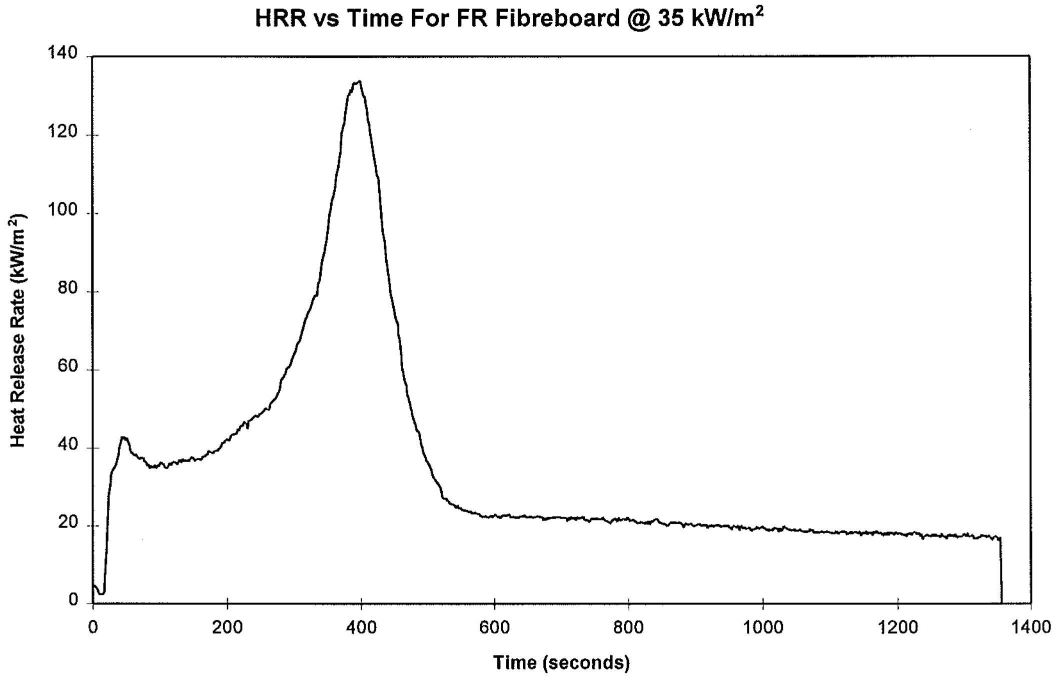
EXP2A.csv	**EXP2B.csv**
FR Fibreboard, 30 kW/m2	FR Fibreboard, Observed
288	288
3.44	3.44
2.809	1.942
1	1
0.405	0.405
1.3	1.3
0.17	0.17
2.945	2.945
5.185	5.185
2.0608	2.0608
150.2	150.2
45.1722	45.1722
58.4837	58.4837
14	14
4.2	4.2
0	0
0.01	0.01
0.25	0.25
60	60
85.8538	85.8538
0.0667	0.0667
0.667	0.667
45362	45362
404.4	404.4
2.2	2.2
2.24	2.24
3.16	3.16
2.73	2.73
30	30
30000	30000
483	483
5	5

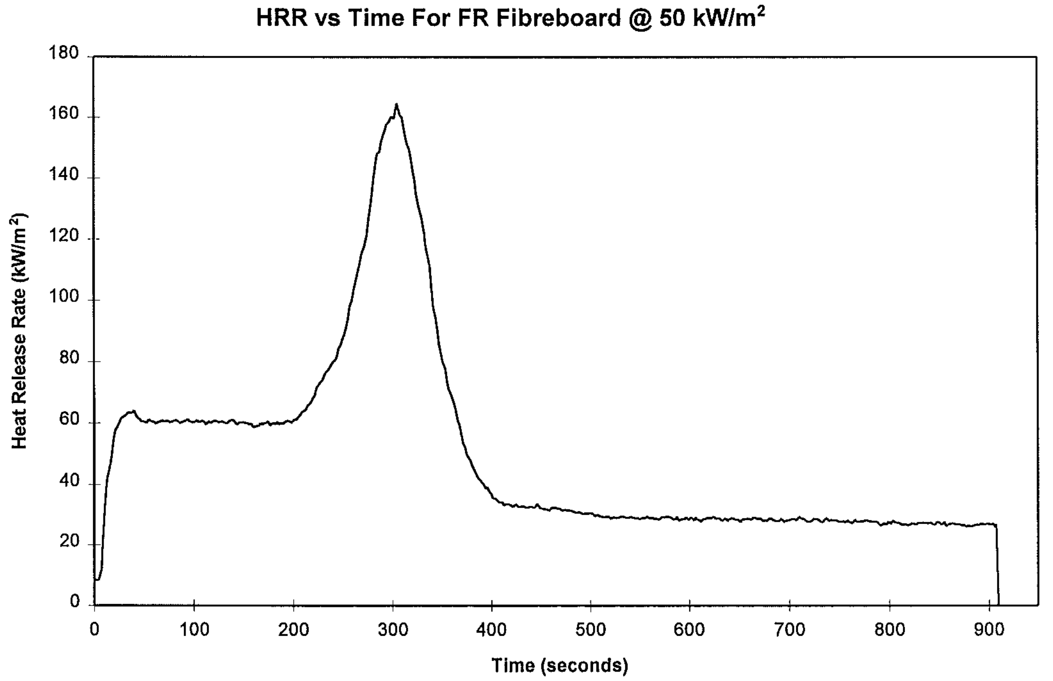
EXP2C.csv	**EXP3A.csv**
FR Fibreboard, Quintiere	Hardboard, Quintiere
288	291
3.44	3.44
0.46	1.87
1	1
0.405	0.405
1.3	1.3
0.17	0.17
2.945	2.945
5.185	5.185
2.0608	2.0608
150.2	182.7
45.1722	45.1722
51.1816	53.973
14	15
4.2	3.2
0	0
0.01	0.01
0.25	0.25
60	60
85.8538	85.8538
0.0667	0.0667
0.667	0.667
45362	62782.9
628	571
2.2	4.5
2.24	2.24
3.16	3.16
2.73	2.73
30	30
30000	30000
483	443
5	5

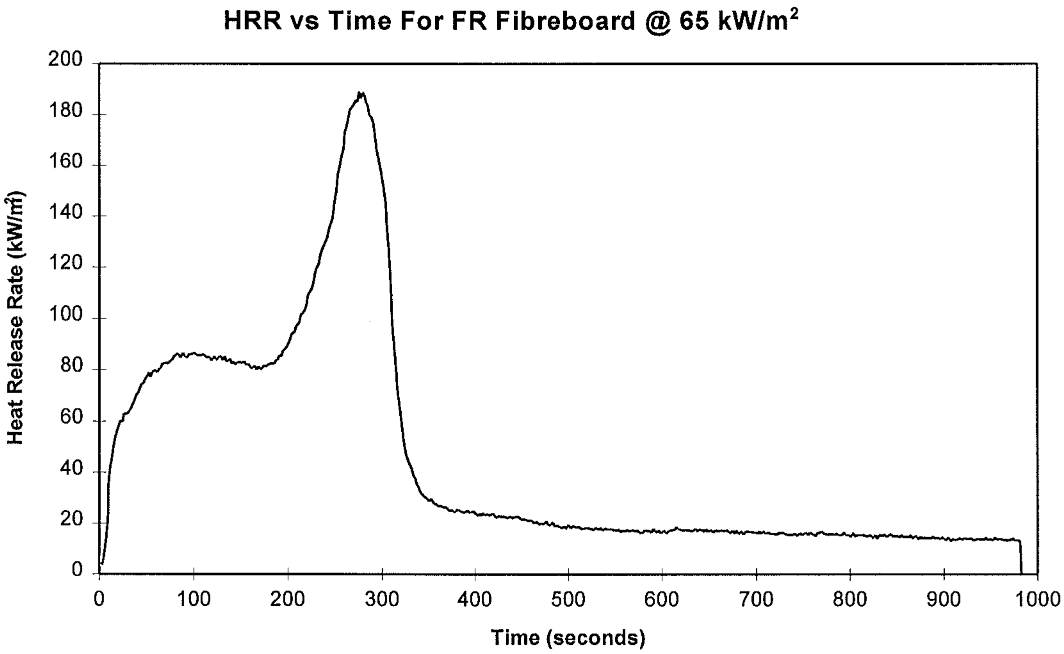
EXP3B.csv	**EXP4A.csv**
Hardboard, 30 kW/m2	Gypsum Plasterboard, Swedish (s4)
291	290
3.44	3.44
2.055	0.515
1	1
0.405	0.405
1.3	1.3
0.17	0.17
2.945	2.945
5.185	5.185
2.0608	2.0608
182.7	100
45.1722	45.1722
57.3901	42.8142
15	7
3.2	4.8
0	0
0.01	0.01
0.25	0.25
60	60
85.8538	85.8538
0.0667	0.0667
0.667	0.667
62782.9	2092.8
463.2	742
4.5	14.7
2.24	2.24
3.16	2.73
2.73	3.16
30	30
30000	30000
443	653
5	5

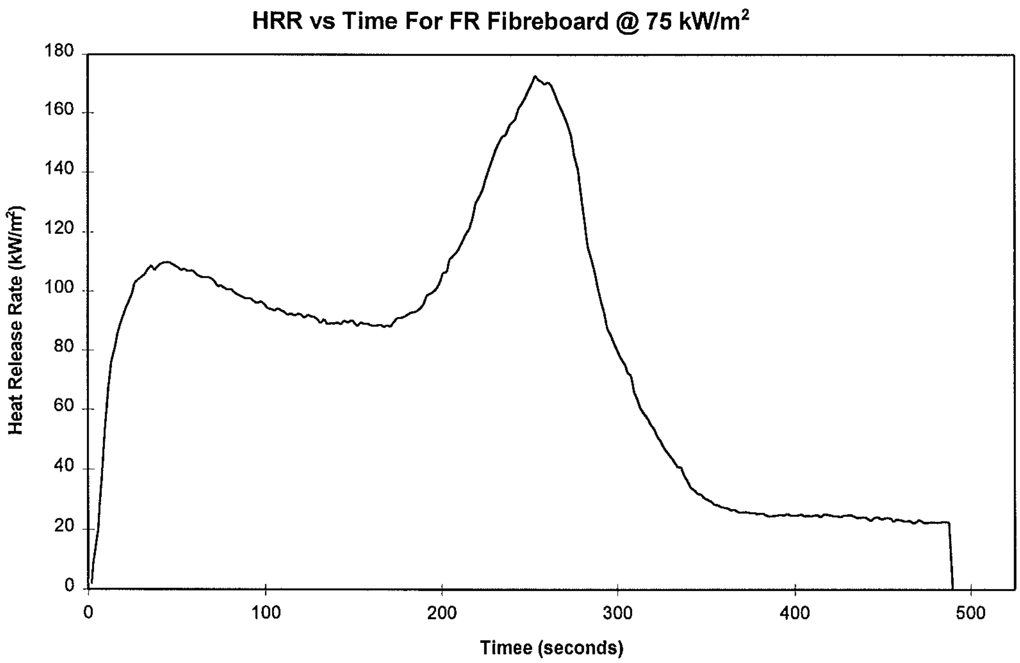
A6. APPENDIX 6: CONE CALORIMETER OUTPUT DATA

The following are the cone calorimeter ouput HRR graphs for the FR Fibreboard and Hardboard, the two experimental materials tested specifically for this research program at BRANZ.

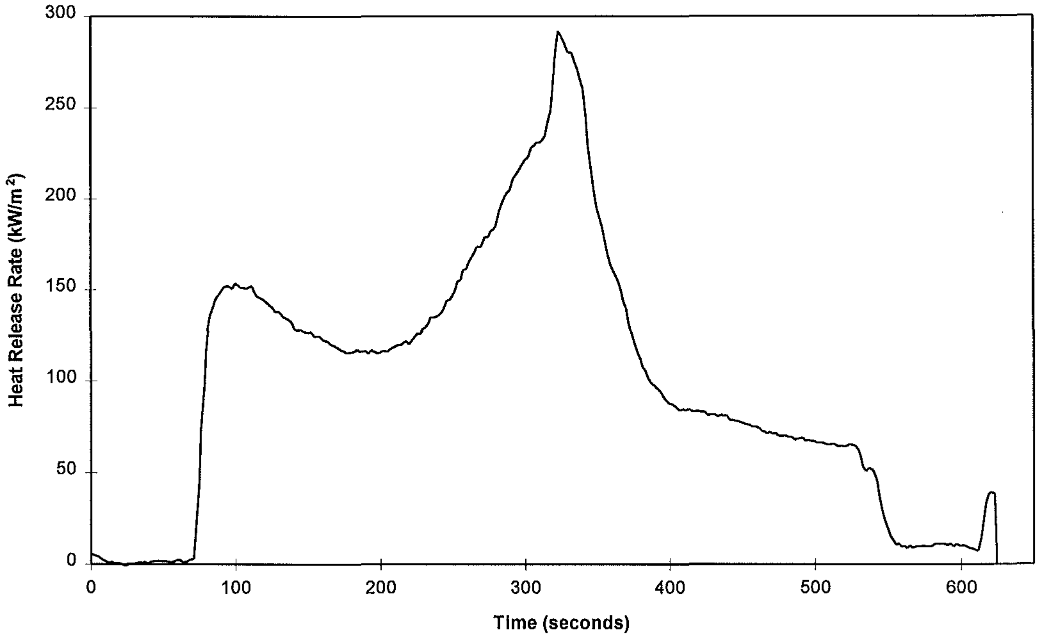




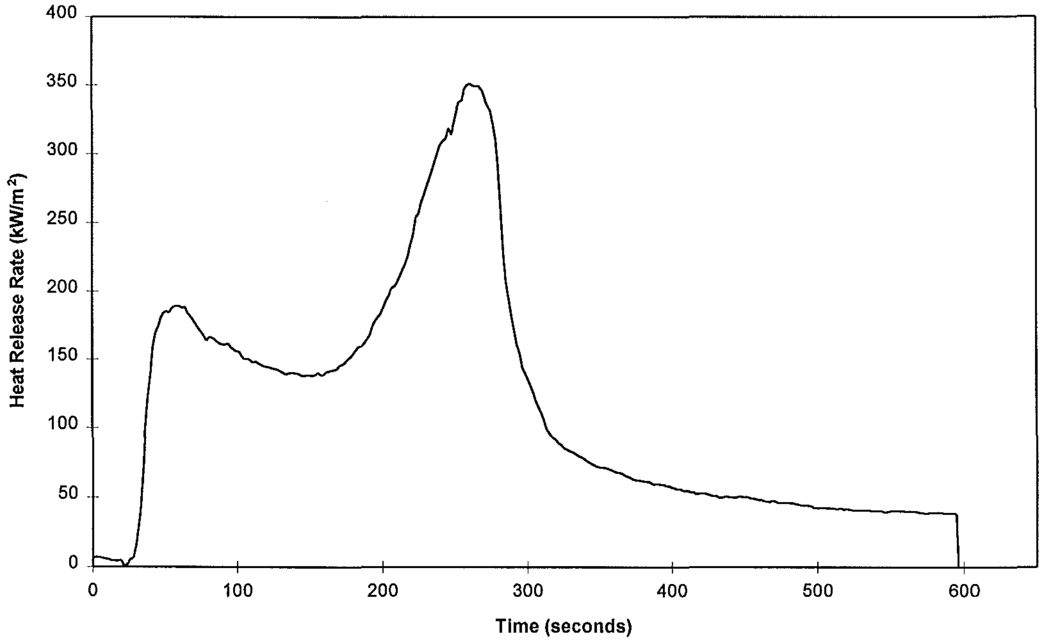

HRR vs Time For FR Fibreboard @ 65 kW/m2
Heat Release Rate (kW/m2)
200
180
160
140
120
100
80
60
40
20
0
0
100
200
300
400
500
600
700
800
900
1000
Time (seconds)


HRR vs Time For FR Fibreboard @ 75 kW/m2
Heat Release Rate (kW/m2)
180
160
140
120
100
80
60
40
20
0
0
100
200
300
400
500
Timee (seconds)

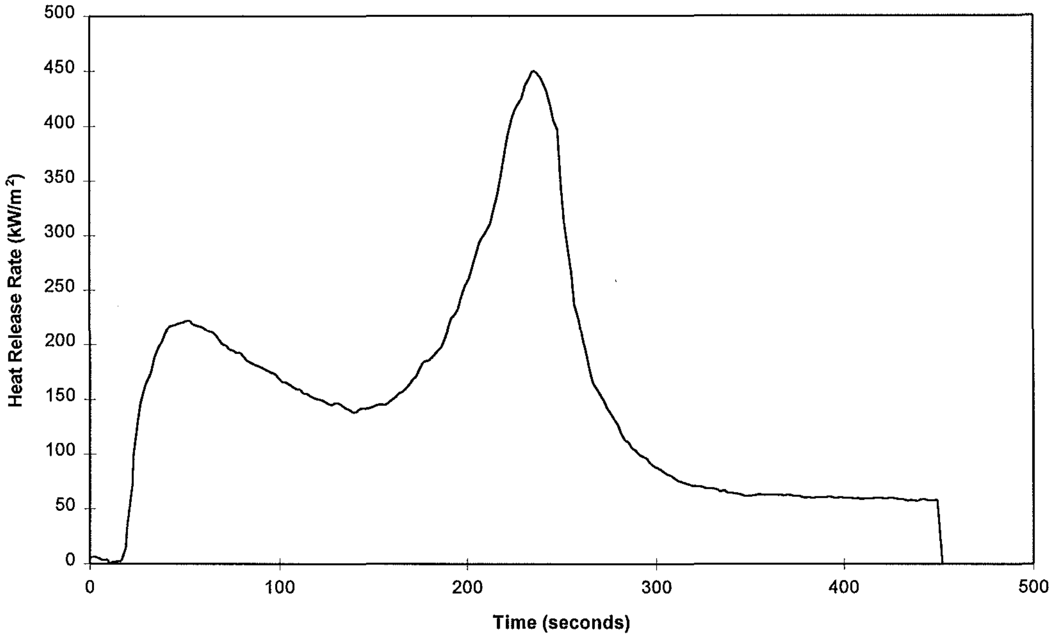
HRR vs Time For Hardboard @ 35 kW/m²



HRR vs Time For Hardboard @ 50 kW/m²



HRR vs Time For Hardboard @ 65 kW/m^2



HRR vs Time For Hardboard @ 75 kW/m^2